Bulletin
of
The Geological Society of America

VOLUME 70 September 1959 NUMBER 9

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Subscription $15.00 per year.
Printing Office: Mt. Royal & Guilford Aves., Baltimore 2, Md.
Communications for publications should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117 Street, New York, N. Y.
Please give notice of change of address 4 weeks in advance. Claims for nonreceipt of the Bulletin of a given month must be sent to the Secretary of the Society before the end of the second succeeding month.

Second-class Postage paid at Baltimore, Md.
Accepted for mailing at special rate of postage provided for in Section 1103
Act of October 3, 1917, authorized on July 8, 1918.

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SECRETARY'S NOTE

Separates of the *Geochemical table of the elements for 1959*, accompanying the paper by Jack Green in this issue, are available at $1.00 per copy (unfolded, in tubes). Please send orders with remittance to The Geological Society of America, 419 West 117 Street, New York 27, N. Y.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 70, PP. 1127–1184, 1 FIG. SEPTEMBER 1959

GEOCHEMICAL TABLE OF THE ELEMENTS FOR 1959

BY JACK GREEN

ABSTRACT

The geochemical table of the elements for 1959 (with French, German, Russian and Spanish keys), cast in the framework of the conventional periodic table, contains the following data for each element:

Geochemical character.

Weight and structure: atomic number, atomic weight, weight of 1 atom, and electronic-shell structure.

Size and charge: atomic, ionic, and miscellaneous radii, atomic and ionic volumes, lattice-energy coefficients, ionization potentials, and radius ratios. Ionic radii are adjusted for various co-ordinations of each ion.

Isotopic: naturally occurring isotopes with per cent abundance, half lives, and type of radiation decay.

Nuclear: thermal neutron-capture cross section and nuclear spin in multiples of $h/2\pi$.

Thermodynamic: standard heat of formation (gas), standard free energy of formation (gas), logarithm of equilibrium constant (gas), and entropy at 25°C. (gas and solid).

Mineralogic: common or geochemically significant minerals with per cent element contained.

Value: range of cost in United States dollars per unit weight or volume of reagent-pure element.

Abundances in grams per metric ton (printed in green overprint)*:* abundances in sedimentary, metamorphic, igneous, and miscellaneous rock types (34 possible categories), in sea water (with transfer percentage), in iron, sulfide, and silicate meteorite phases), and in the universe (including volatiles) are tabulated. Where possible, number of individual analyses and standard deviations for the arithmetic average are given as superscripts and subscripts respectively. Boldface indicates a general or global average; averages in lightface are local or specific with respect to area and/or time.

Series of geochemical interest: electromotive, oxidation-reduction, electrochemical equivalents, entropy of ions in aqueous solution, cation-field strength, ionic replacement, electronegativity, reaction, zoning, affinity for sulfur in melt, solubility of sulfides, exchangeability in clays, and hydroxide precipitation pH's. Ionic potential and co-ordination data are graphed.

A post-1953 bibliography of nonradiogenic isotope abundance data and a listing of abundances of elements in soils and igneous rocks, not included in the table, are included in the text.

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Introduction

The geochemical table of the elements for 1959 summarizes data on geochemical parameters which have appeared since 1953. Progress in geochemistry has made the 1953 geochemical table (Green, 1953) obsolete. Refinements of atomic weights and radii, new data on abundance of rocks and minerals, and additional nuclear and electrochemical values are included in the table for 1959. Data have been selected from work by recognized specialists in earth sciences; the responsibility of choice and, in rare cases, screening of the numbers rests with the author. The abundance data herein are restricted to the lithosphere, the marine hydrosphere, and the cosmosphere exclusive of tektites and achondrites. Abundances of elements in the biosphere and atmosphere are not included.

The general geochemical behavior of the elements in Table 2 is coded by color and style of letter. Classes so identified include the lithophile elements associated with silicon; the sulfophile elements associated with sulfur; the siderophile elements associated with iron; the biophile elements associated with carbon; and the atmophile elements associated with oxygen and nitrogen. Dispersed elements (Vernadsky, 1924, p. 61–64), included mostly for historical reasons, are indicated by italicized atomic numbers.

Space does not permit full amplification of details or evaluation of analytical techniques. This report indicates the sources from which the geochemical table has been compiled. It is an index to a small part of recent geochemical literature. Because of the wide audience to which this paper is presented, much supplementary information is referred to.

Acknowledgments

It is presumptuous for one person to attempt compilation of the geochemical parameters listed on Table 2. The compiler has leaned heavily on several specialists who have graciously made their unpublished data available. Dr. J. A. S. Adams contributed data on abundances of potassium, uranium, and thorium in sediments and also critically reviewed the manuscript. Dr. M. Fleischer aided materially in selection of mineral assemblages and made available his compilation of G1 and W1 abundance data. Dr. E. D. Goldberg furnished estimates of abundances of elements in the marine hydrosphere. Dr. W. T. Holser selected and computed most of the abundance data on beryllium. Selected published articles unobtainable in American libraries at the time of writing were thoughtfully provided by Drs. J. Jedwab of Brussels and A. S. Povarennykh of Krivoy Rog. These people have lessened the author's task and improved the quality of the compilation. Finally, California Research Corporation kindly supplied the drafting services and facilities necessary to make Table 2 a reality.

Atomic and Elemental Constants

Atomic Weights and the Physical and Chemical Scales

Table 2 shows new values accepted by the International Atomic Weights Committee (Wichers, 1956, p. 3235–3237) for the elements Ni, Pd, In, Xe, Sm, Gd, Dy, Er, Hf, W, Re, and Pt. Members attending the Nineteenth Conference of the Commission on Atomic Weights of the International Union of Pure and Applied Chemistry (Paris, July 16–25,

1957) agreed that no changes would be made in the values for atomic weights recommended by the Commission in 1955. For work of highest accuracy, however, Wichers (1958) recommends that the following physically measured atomic weights be used: As, 74.92; Y, 88.91; Pr, 140.91; Bi, 208.99. Detailed information on atomic weights of 22 monoisotopic elements (Duckworth, 1954) may be compared with atomic weights computed by physical measurements (Wapstra, 1957).

Table 2 lists isotopes of radioactive elements in brackets, whether they occur in nature or are known only through synthesis; these elements are Tc, Pm, Po, At, Rn, Fr, Ra, Ac, Pa, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, and No. The listed isotope (selected by the 1957 Commission on Atomic Weights) may be either the one of longest known half life or, for those marked with an asterisk, a better known one. Atomic weights, however, were retained in 1957 for uranium and thorium. Tc, Pm, Fr, and the post-Pu elements probably do not occur in nature. The accepted variation of ±0.003 for S is not shown on the table. Boggs (1955) discusses other atomic-weight variations in nature.

Atomic weights in Table 2 are on the chemical scale based on an atomic weight of 16 for oxygen. The physical scale is based on an atomic weight of 16 for O^{16}. Wichers (1956, p. 3237–3240) and Scott and Ware (1957) point out the advantages of adopting the element fluorine (atomic weight, 19) as basis for both the chemical and physical scales. This would result in a change upward of 1 part in 25,000 (+0.0041 per cent) for existing values based on the chemical scale—a negligible change—and a change downward of 1 part in 3000 for values based on the existing physical scale. Other scale-change proposals and the relative shift of numbers with respect to the chemical scale include: carbon 12 = 12 (−0.0043 per cent); nitrogen 15 = 15 (−0.0050 per cent); oxygen 17 = 17 (+0.0008 per cent); oxygen 18 = 18 (+0.0004 per cent). These proposals are detailed by the International Union of Pure and Applied Chemistry (1957). The scale based on carbon 12 suggested by Dr. A. O. C. Nier appears to be the most suitable scale for both physicists and chemists (Mattauch, 1958). The geochemist, dealing with both chemical and physical constants, would undoubtedly find a common basis for both systems convenient.

Avogadro's number—taken as 6.02403×10^{23} (Straumanis, 1953; 1954)—was used to compute the weight of one atom of each element.

The Periodic Table as a Medium for Illustrating Geochemical Parameters

Numerous authors have used the Mendeleev periodic table or modifications of it to illustrate geochemical features. It is therefore convenient to use such a universally accepted, genetically significant framework in which to include radii, mineralogical, abundance, and other data. In the present table, subgroup offsets are emphasized, as are the lanthanide and actinide groups. The newest synthetic elements (Ghiorso and Seaborg, 1956) are included for completeness, with one empty space left to complete the 5 f electron shell. Lepsius and Asunmaa (1954) and Asunmaa and Lepsius (1955) have contributed to knowledge of the periodic table as it relates to atomic nucleii and electron shells. Specific details of the periodic system such as length of the periods (Tudos, 1954; Markevich, 1952; Uklonskiĭ, 1954) are implied in a paper on the mathematical basis of the periodic table by Bolivar *et al.* (1957). Students interested in the historical (Tomkeieff, 1958) and genetic (Meyer and Rosenqvist, 1949a; 1949b) evolution of the periodic table may find Derzhavin's (1955) graphical treatment of variations of this table of value.

New periodic tables are no novelty (Ionescu, 1956; Sanderson, 1956; Al'banskiĭ, 1950; Tomkeieff, 1954; Bedreag, 1952; Carobbi, 1947; Grebe, 1958; Kornilov, 1957), and the merits of each depend on the use intended. General papers (e.g. Shchukarev, 1954, and Semenchenko, 1952), which emphasize the periodic table as basic to modern chemistry supplement a specific paper which relates the periodic table to geochemistry by Sokoloff (1954).

Periodicity of the following parameters can be displayed on the periodic table:

(1) Lattice types and packing densities (Tomkeieff, 1956b)
(2) Heats of formation (Shishokin, 1954)
(3) Electron-shell contraction (Lakatos, 1956)
(4) Thermodynamic properties (Lakatos, 1955)
(5) Compressibility (Egyed, 1954)
(6) Density (V. I. Lebedev, 1948)
(7) Entropy of fusion, heat of vaporization (Gertsriken, 1956)
(8) Atomic heat of transition metals (Lakatos, 1957)

(9) Ionization potential (Cartledge, 1928)
(10) Liquid-state structure (Golik, 1957)
(11) Optical properties of glasses (Kühne 1956)
(12) Melting point (Voronet, 1957)
(13) Abundance of isotopes (Harkins, 1917; 1931; Fersman, 1932)
(14) Ore-element assemblages (B. W. Brown, 1956)
(15) Atomic volumes (Zaslavskiĭ, 1931)
(16) Ionic radii (Berkenheim, 1929)

This listing, which represents a fair sampling of recent literature and a few old classics, justifies the use of the periodic system as format for Table 2.

Atomic Radii as Related to Bond Type and Co-ordination

Except for the miscellaneous radii, data on a given radius in Table 2 apply to the other data on the same line. For example, the charge, radius, co-ordination, ionic volume, radius ratio, lattice-energy coefficient, and ionization potential of the lithium ion are all on the same horizontal line.

Atomic radii include ionic radii, metallic-ion radii, covalent or tetrahedral radii, and hydrated-ion radii. All degrees of sophistication in the use and application of these radii exist. Bonding energies vary with environmental conditions, resulting in a continuum of radii only ideally intensified into the ionic, the homopolar, the metallic, and the van der Waal types (Povarennykh, 1956a; 1956b; Evans, 1939, p. 41; Tomkeieff, 1955; Fyfe, 1951). Therefore, this section may perhaps be incorrectly placed under atomic and elemental "constants." Radii also vary with co-ordination (Pauling, 1948a, p. 367). Relationships between atomic and ionic bonds and bond types as related to co-ordination are discussed by Somayajula and Palit (1957) and Batsanov and Pakhomov (1957). Generally, the lower the co-ordination number and/or the more ionic the bond, the smaller the radius.

If ionic-radii determinations for specific elements are omitted, there are about 14 sets of ionic radii, with certain ones preferred by different specialists:

Bragg (1920)	Computed from X-ray data of crystals of elements and crystals of ionic compounds
Wasastjerna (1923)	Derived from ionic refractivity values (*see* Batsanov and Ruchkin, 1956)
Goldschmidt *et al.* (1926)	Derived from empirical data obtained from interionic-distance measurements
Pauling (1927)	Calculated from empirical data by use of electronic theory of atomic structure
Zachariasen (1931)	Calculated from consideration of electrostatic forces
Wyckoff (1931, p. 192–193)	Calculated on basis of interionic distances in alkali halides
Kapustinskiĭ and Veselovskiĭ (1934)	Based on thermochemical information
Jensen, Meyer-Gossler, and Rohde (1938)	Calculated using wave mechanics
Kordes (1940)	Calculated from atomic physical properties
Stockar (1950)	Calculated from empirical formulae
Ahrens (1952; 1953)	Based on ionization-potential data
Yatsimirskiĭ (1953)	Based on ionization-potential data
Belov and Bokiĭ (1954)	Derived from semi-theoretical considerations — intermediate between Pauling's and Goldschmidt's data
Povarennykh (1956a)	Obtained from electronegativity parameters

More advanced treatment of ionic radii in specific ion combinations is given by Fyfe (1954), Vendel and Frauenhoffer (1955), and Arnold (1956).

Because any given ionic radius depends on the co-ordination-bond type continuum of its environment, an attempt was made to adjust the ionic radii for one of these variables—the co-ordination. The ionic radii in Table 2 are the Ahrens (1952) radii so adjusted for the co-ordination for each ion. The radii are based on a radius of 1.40 Å, which is that of oxygen when it is not significantly polarized (Ramberg, 1954; Batsanov, 1956). Using Pauling's (1948a, p. 368) ionic–radius-change factors and a Born exponent of 9[1] (Fig. 1), one can modify radii calculated for sixfold co-ordination according to the specific co-ordination preferred by each ion. The change is small for co-ordinations 4 and 6 but is appreciable for co-ordinations 10 or 12. For example, Cs in

[1] The Born exponent is a function of the compressibility of a substance. For crystalline material, the Born exponent approximates a value of 9.

sixfold co-ordination has an ionic radius of 1.67. But Cs does not occur in sixfold co-ordination in nature. Its radius for the co-ordination in which it occurs is 1.85 Å when multiplied by the appropriate radius-change factor.

As a check against the ionization–potential-derived radii, all the Ahrens sixfold and normalized-sixfold radii were used in calculation of mass per cubic angstrom. The ionic mass per cubic angstrom, elemental mass per cubic angstrom, and liquid and solid measured densities were plotted against atomic number. An expected periodicity was observed for the ionic mass per cubic angstrom with a serial divergence from the measured elemental densities with decrease in the ionic character of the element. Relatively smooth curves were obtained for ions of like charge except for Cr^{+3}. The relative masses per cubic angstrom for +3 ions neighboring chromium are: Sc, 20.2; Ti, 26.0; V, 30.0; Cr, 49.7; Mn, 45.6; Fe, 50.9; and Co, 56.3. Adjustment of Cr^{+3} to the smoothed mass per cubic angstrom curve would give a radius of 0.69 Å for Cr^{+3}. Because the atomic masses in the germanium-chromium region may be used with reasonable confidence (Duckworth, Kerr, and Taylor, 1955), the ionization potential for Cr^{+3} may need review. The old radius of Cr^{+3} (0.63 Å) is retained pending this.

Atomic radii are from Goldschmidt (1928; 1954, p. 119). Additional rare-earth atomic radii are from Herrmann, Daane, and Sped-

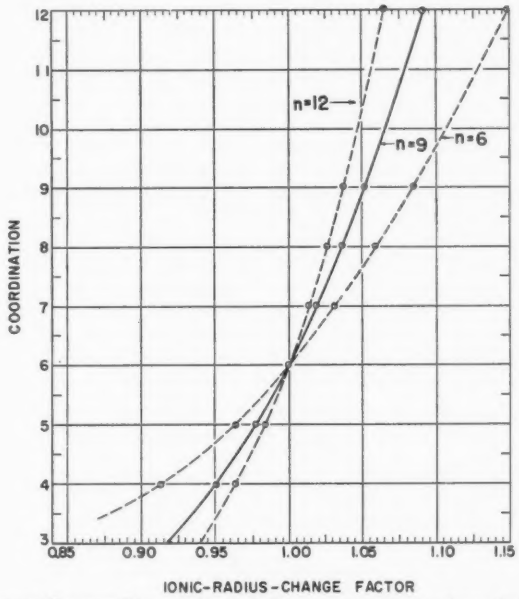

FIGURE 1.—IONIC-RADIUS-CHANGE FACTORS VERSUS CO-ORDINATIONS FOR BORN EXPONENTS 6, 9, AND 12 (After Pauling, 1948, p. 368)

The following ionic radii were not obtained from the original reference (Ahrens, 1952, p. 168–169):

Ac^{+4} was derived by extrapolation of Ahrens' sixfold radii for Am^{+4}, Pu^{+4}, Np^{+4}, U^{+4}, Pa^{+4}, and Th^{+4}. This extrapolated radius was then adjusted for eightfold co-ordination. Respecting the criticism of W. U. Ault and M. K. Carron (Personal communication), the compiler has modified the value of Pm^{+3} from that listed in Ahrens (1952, p. 169). Th^{+3} and U^{+3} were derived by extrapolation of Ahrens' sixfold radii for Am^{+3}, Pu^{+3}, Np^{+3}, Pa^{+3}, and Ac^{+3}. Both extrapolated radii were then adjusted for eightfold co-ordination.

Normalizations to the Ahrens' radii were made for Eu^{+2} and Yb^{+2} from the Goldschmidt (1954, p. 89) radii, which are based on a radius of 1.33 Å for oxygen. Normalizations were done using proportionality ratios for the elements in question in the Goldschmidt and Ahrens radii sets. These normalized radii were then adjusted for co-ordination.

ding (1955, p. 46–47). Radii for the following ions in twelvefold co-ordinaton are averaged from radii calculated from X-ray data from atoms in the basal plane and between layers: La, Ce, Pr, Sm, Gd, Tb, Ho, Er, Tm, Lu, and Eu, the last for eightfold co-ordination. All other rare-earth metallic radii are from Klemm and Bommer (1937), with duplication of data for twelvefold-co-ordinated Nd, Dy, and Yb.

Some specific examples of bonding-radius relationships merit mention. In particular, the cause of different bond types on semi-conductor surfaces is discussed by Wolkenstein (1957) and Mooser and Pearson (1956). Germane to mineralogical and petrological studies are papers by Ramberg (1952b), Povarennykh (1957), Vistelius (1956), and Carron, Mrose, and Murata (1958).

Miscellaneous radii, also listed in Table 2, do not relate to other ionic parameters. This column is to be read vertically and is therefore set off from the other columns. The miscellaneous-radii column contains tetrahedral radii, hydrated radii, and normalized radii in fluorides, oxides, and sulfides.

Radii of atoms in covalent compounds—tetrahedral radii—are radii which apply both to interatomic distances in the molecular arrangements of nonionic inorganic and organic compounds and to covalent bonds in crystals up to a co-ordination number of 4. These radii, noted by a subscript T, are from the compilation by Goldschmidt (1954, p. 109) from Pauling and Huggins (1934).

Hydrated radii, from Ovchinnikov (1956, p. 143), are radii of the hydrated ions and are noted by a subscript H. They may be approximated by the formula:

$$r = \frac{n_e C_0 F}{6\pi\eta u}$$ Brodskiĭ (1948, p. 613)

where

r = radius of hydrated ion
n_e = valence of the ion
C_0 = elementary electrical charge
F = Faraday's constant
η = viscosity of the solvent
u = absolute mobility of the ion

Grim (1953, p. 148) lists additional hydrated-ion radii from other sources. Welby (1958) discusses the role of hydrated radii and ionic potentials in Gulf of Mexico sediments.

The radii for fluorides, oxides, and sulfides are modified from Povarennykh (1956a, p. 1168) in an attempt to normalize to Ahrens' radii. However, this normalization is based on the assumption that the effective radii computed by Povarennykh correspond in a relative sense to the ionic radii derived from ionization potentials. Povarennykh obtains his set of radii by adopting the metallic radii of Na and K as a starting point. Knowing the degree of covalence of their bonds in fluorides, one can obtain effective ionic radii. An example of the normalization is given for calcium.

	Ionic radius	Covalent Metallic	Difference	Radius in fluorides	Radius in oxides	Radius in sulfides
Povarennykh	0.92	1.97	1.05	0.99	1.12	1.43
Ahrens (ionic radius only)	0.99	1.97	0.98	..	..	..
Modified to Ahrens' radii	0.99	..	..	1.06	1.18	1.47

Fluoride	*Oxide*	*Sulfide*
$0.07/1.05 \times 0.98 = 0.07$	$0.20/1.05 \times 0.98 = 0.19$	$0.51/1.05 \times 0.98 = 0.48$
$0.07 + 0.99 = 1.06$	$0.19 + 0.99 = 1.18$	$0.48 + 0.99 = 1.47$

Until more rigorously normalized and evaluated, these miscellaneous radii should be used only as an approximate guide to radii in fluorides, oxides, and sulfides.

Lattice-Energy Coefficients in Geochemical Processes

Lattice energy is the energy absorbed when a mole of a crystal is dispersed into infinitely separated ions. The consideration of lattice energy as a tool to a better understanding of geochemical processes was given impetus by Fersman (1935a; 1935b) and has recently been re-examined by Leutwein and Doerffel (1956), who have recalculated many of the earlier data using modern radii and thermodynamic parameters. Their data are used in Table 2. For simple binary compounds, such as NaCl or MgO, the lattice energy (U) may be calculated from the following formula:

$$U = \frac{NAz_c z_a}{r}\left(1 - \frac{1}{n}\right)$$

where

U = lattice energy
N = Avogadro's number
A = a constant characteristic of the type of crystal structure (Madelung constant)
z_c, z_a = charge on the cation and anion respectively
r = shortest anion-cation distance
n = a factor (usually around 10) dependent on internuclear repulsion.

Yatsimirskiĭ (1956) has computed lattice energies for more complex compounds.

The lattice-energy coefficient is an empirical constant for each element, representing the contribution of that element to the lattice energies of its compounds. By adding lattice-energy coefficients and multiplying by a constant, one may obtain the lattice energy of the compound in question. As a starting point, Fersman used the approximately equal cation-anion radii in the compounds potassium fluoride and strontium oxide. By distributing the known lattice energies of these two compounds uniformly over cation and anion, he obtained four EK (energy coefficients), which he used to obtain additional EK's. The valence-energy coefficient (VEK) is simply EK divided by the charge of the ion (Fersman, 1936). By plotting VEK against charge, a diagram similar to the ionic-potential diagram is obtained; the abscissa ranges from 0 to around 500. Such a diagram with discussion is shown by Leutwein and Doerffel (1956, p. 78).

The application and limitations of lattice energies for polymorphs of the same substance and compounds containing amphoteric elements are discussed by Mason (1958, p. 79). The double role of aluminum in silicates is well known. Lattice energies computed for silicates in which aluminum is contained in the SiO_4 tetrahedra are anomalous. In the reaction series (Table 2), relative lattice energies, from Leutwein and Doerffel (1956, p. 93), are given in parentheses. These authors point out that lattice-energy coefficients yield inaccurate values in minerals in which aluminum plays a double role. (*Compare* feldspar and pyroxene with quartz in the reaction series.) However, they emphasize that the lattice-energy coefficients of the individual ions should be considered. For example, the lattice-energy coefficient of Si^{+4} (2500) is greater than that of Al^{+3} (1280). This means that SiO_4^{-4} tetrahedra would form more readily than AlO_4^{-5} tetrahedra. However, if both complexes existed in a magma, the AlO_4^{-5} tetrahedra would tend to crystallize out first, because the lattice energy of AlO_4^{-5} is greater than that of SiO_4^{-5} (Leutwein and Doerffel, 1956, p. 75, 93–94). These data and application of lattice energies to problems of mineral paragenesis, given in the last-mentioned reference, are critically examined by Szádeczky-Kardoss (1958b).

Additional parameters related to lattice energies include:

Ion potentials	Cartledge (1928)
Cation-field strength (under Series, Table 2)	Dietzel (1942)
Ionization potentials	Ahrens (1953)
Energy index	Gruner (1950)
Bond energy	Huggins and Sun (1946)
Ion density; cation and anion potentials	Szádeczky-Kardoss (1953–1954, 1954, 1955a)
Bonding energy	Keller (1954)
Index of diadochy (noted as Index of Ionic Replacement under Series, Table 2)	Hori (1954)

Lattice-energy coefficients deserve more attention in interpretative petrology.

Abundance of Isotopes and Thermal Neutron-Capture Cross Sections

Several excellent texts and reviews on radiogenic and nonradiogenic isotope distributions and abundances have appeared since 1953 (Wanless, 1957; Faul, 1954; Rankama, 1953; 1954a; Lopez de Azcona, 1953; 1955; Ingerson, 1953—*see also* Rankama, 1954i; Ahrens, 1957a; Joliet, 1957; Vinogradov, 1954a; 1958; Jensen, 1953b; Aprile, 1955; Vitoria, 1955; Koana, 1956; J. Silverman and Cohen, 1956; Craig and Boato, 1955). Geiss (1957) has considered the specific application of isotopes to the study of meteorites, and Jensen (1953a) discusses isotopic methods in study of fluid inclusions. Bogomolov (1955) briefly discusses ground-water movement from the standpoint of isotopes. Herrera (1954) applies isotopic techniques to problems of petrogenesis. Senftle and Bracken (1955) deal with the theoretical effect of diffusion on isotopic-abundance ratios in rocks and associated fluids.

The per cent relative abundance of isotopes in Table 2 is the percentage of stable nuclides present in naturally occurring elements and is expressed in percentages in numbers of atoms and not by weight. The isotopic abundances

and neutron-capture cross sections in Table 2 are from Lange (1956, p. 114–149). The information was originally compiled by G. Friedlander and M. Perlman and revised by J. R. Stehn and E. F. Clancy of the Knolls Atomic Power Laboratory in the course of making the 1956 revision of the General Electric Company's Chart of the Nuclides. Many of the isotopic-abundance and thermal neutron-capture cross section data have been rounded to two or three digits from earlier compilations by Hollander, Perlman, and Seaborg (1953) and Hughes and Harvey (1955), respectively. Additional compilation notes on isotope abundances appearing in Table 2 are:

The per cent abundances of Ge and Si (but not Hf) are rounded from Reynolds (1953a); the per cent abundance of oxygen is quoted by Stehn and Clancy as given by Nier (1955) and Scolman, Quisenberry, and Nier (1956). The abundance data shown for Be^{7} are taken by this compiler from J. R. Arnold (1954, cited as a personal communication *in* Lopez de Azcona, 1955) and He^{4} from Lopez de Azcona (1955). Abundance data for Ru are from Sites (1956, p. 152) and should probably be quoted to three digits to be consistent with other abundance data in the table. The per cent abundance data of Pd to the nearest tenth have been rounded by Stehn and Clancy from Sites, Consolazio, and Baldock (1953); abundances for Ta are quoted verbatim by Stehn and Clancy from White, Collins, and Rourke (1955, p. 566–567); abundances for Ir are taken by this compiler from Sites (in preparation, *cited in* Union Carbide Nuclear Company catalog, 1957, p. 29). In the last reference and in Mohler (1955) and Dibeler (1956), information is given regarding availability of specific isotope species and standards.

Kohman (1953) discusses the search for new natural radioactivities including Ca^{48}, V^{50}, Zn^{96}, Mo^{100}, Cd^{113}-In^{113}, Sb^{123}-Te^{123}, Te^{130}, La^{138}, Nd^{150}, and natural alpha activities in W^{180} or W^{178}, Nd^{144}, Bi^{209}, and Pb^{204}.

A post-1953 nonradiogenic-isotope bibliography, exclusive of entries on methodology or instrumentation, is given under each element in the section listing abundances of elements by element.

The nuclear mechanical moments or "spin" in $h/2\pi$, in which h is Planck's constant, are from Klinkenberg (1952) and appear as black superscripts above the isotope. Nuclear moments for Gd are derived from Low (1956).

Thermodynamic Data

Standard heat of formation (gas), standard free energy of formation (gas), logarithm of equilibrium constant of formation (gas) and entropy at 25°C. (gas and solid, with the exception of Hg) are from Lange (1956, p. 1579–1630). Entropies for carbon are those of graphite. Under phosphorous and tin, entropy at 25° C. (solid) is for white phosphorous and the tetragonal phase of tin, respectively. These data are amplified in Rossini *et al.* (1952), Eitel (1952), Latimer (1954), and Stull and Sinke (1956). G. J. F. Macdonald (1954, unpub. PhD thesis, Harvard Univ.) reviews geologically important thermochemical data, including heat of formation, entropies, and heat capacities of minerals. Changes of thermochemical properties of minerals as a function of the composition of the mineral are also considered. The data are documented with 236 references. Saull (1955), Garrels (1957), and Ramberg, Bennington, and Weeks (1957) apply some of these thermodynamic parameters to geologic processes.

Distribution and Abundance of Elements in the Geochemical Spheres

Geochemistry Texts and Current Reviews

The compiler has drawn heavily upon standard geochemistry texts and current reviews. These provide definitive and thorough appraisals of abundance data. Besides the texts familiar to the English-speaking world—by Rankama and Sahama (1950), Goldschmidt (1954), and Mason (1958)—there are texts by Saukov (1953) and Miyake (1954) and a review paper by Yamasaki (1956). Review articles appearing in The Physics and Chemistry of the Earth series (Ahrens *et al.*, 1956; 1957) have been used in compilation of data for Ga, In, and Tl (Shaw, 1957) and Cl, I, F, and Br (Correns, 1956). Tomkeieff (1956a, p. 243–246) gives an insight into the Russian geochemical literature. A review of phase diagrams in geochemistry by Schairer (1957) and the annual reports of the Director of the Geophysical Laboratory of the Carnegie Institution warrant mention. The U. S. Geological Survey revision of the Data of Geochemistry (M. Fleischer, *Editor*, in preparation) contains a wealth of detailed and critically selected analytical data. Two recent texts on geochemical prospecting are by Hawkes (1957) and Krasnikov (1957).

Elemental Distributions and Abundances

Papers relating to general elemental abundances in or on the earth are not rare. It is

interesting to compare the abundance figures of the early 1920's (F. W. Clarke and Washington, 1924, p. 34; Vernadsky, 1924, p. 17) with modern compilations (Bayramgil, 1952; Urey, 1952; 1953a, Urbain, 1954; Asimov, 1954; 1956; Blondel, 1954; Fleischer, 1954; 1955; Shimazu, 1955; Vinogradov, 1956; Ahrens, 1957; Levin, 1957; Turekian, in press; Macdonald and Knopoff, 1958). General papers on elemental distributions in rocks and the laws governing them include those by Goldschmidt (1930; 1934; 1937b), Green and Poldervaart (1958), Neumann, Mead, and Vitaliano (1954), Eugster (1955), Koczy (1951), Lur'e (1957), and Stadnichenko (1957), the last with a review of the clarke concept. A selected bibliography of the lognormal controversy includes: Ahrens (1954a; 1954b; 1957b), Chayes (1954), Aubrey (1954; 1955), Miller and Goldberg (1955), Umemoto (1955), Durovič (1957), and Hanya and Sawada (1956). The literature of geochemistry is discussed by M. H. Shera (1955, Unpub. MS thesis, Western Reserve Univ.).

In addition to general texts and review articles, a host of papers also deal with distribution or abundance of a specific element in a given environment or rock type. The selection of the categories in Table 2 excludes the nonmarine hydrosphere, the atmosphere, the biosphere, soils, achondrites, and tektites. Within the remaining categories, there is some question not only as to desirability of the category but definition of the category. For example: is there sense in designating shale as a division for which geochemical abundances are tabulated when indeed, for many elements, marine shales are chemically distinct from nonmarine shales and black shales differ from nonblack shales? Here the compiler stands in danger of masking real and significant differences in different hydrolyzate environments. That differences do exist has been demonstrated by Degens (1957), Degens, Williams, and Keith (1957), and others. Again, for schists, S. R. Taylor (1955) emphasizes chemical differences between schists derived from basalts and schists derived from sedimentary materials. The category must be defined carefully for intelligent comparison of the data.

Determination of the average is also a problem in a general compilation of this sort. Should the average be calculated with respect to bed thickness, area, volume, time, or combinations of these? Runnels and Schleicher (1956) have compared averages made on the basis of thickness of stratigraphic units with "conventional" averages. They also give two averages for certain constituents. The first is only for those specimens in which the element was determined quantitatively above its detectable limit. The second average is based on all samples, assuming those below the detectable limit to be zero.

As for the effect of time on elemental abundances, comparison of data from one area with those of another is tricky, depending upon sampling and analytical standardization in the areas considered. The Russian workers cited in the footnote to Table 1 and also Okoda (1956) have attempted to interpret elemental abundances in time within a specific area.

These problems are compounded in deciding on sample selection and analysis rejection. What is representative? Log normality is sometimes aided by inclusion of the weathered sample, the leached sample, the hydrothermally and deuterically altered sample, or the secondarily enriched sample. The average for any category can be biased unto distortion if such samples are retained.

Problems exist in the calculation of elemental averages for Recent sediments. Serial or erratic changes in elemental composition from the seawater-sediment interface downward have been recorded by several workers (Pettersson, 1953; Pettersson and Rotschi, 1952; Yalkovsky, 1958). On the other hand, some elements such as U and Th remain almost constant in composition along the length of deep-sea cores (Starik *et al.*, 1958).

The effect of particle size on elemental-abundance statistics has been studied by many people; no generalizations can be made. In one thorough study, sand-, silt-, and clay-size fractions of weathering products of granite, andesite, granodiorite, and basalt were analyzed spectrochemically for the following elements: Si, Al, Fe^{+3}, Mg, Ca, Na, K, Ti, Ba, Co, Cr, Cu, Ga, Mn, Ni, Pb, Sc, Sr, V, Zn, and Zr. No consistent pattern of distribution for most of these elements was observed in the size fractions analyzed (N. M. Short, 1958, unpub. PhD thesis, Mass. Inst. Technology). On the other hand, the preference of certain size fractions of marine sediments for certain elements is well known. Boron distribution in marine clays is an example (Landergren, 1958).

Abundances of the elements in the categories listed in the key to Table 2 are arithmetic averages. A superscript indicates the number of individual analyses. If any or all of the individual analyses are from a composited sample, the

superscript is underlined. A subscript indicates the standard deviation (s):

$$s = \sqrt{\frac{\Sigma(m - M)^2}{n - 1}}$$

in which m = individual analysis
M = arithmetic average
n = number of individual analyses

The significance of superscripts and subscripts in parentheses will be discussed under the heading Shales, Sandstones, and Carbonates.

In rare cases an individual analysis has been rejected by the compiler; the reasons are explained in the alphabetical listing of the elements in the section Abundances of Elements by Element. Most of these are abnormally high values which do not appear to be representative and which would cause the standard deviation to exceed the average. This raises the point of whether the standard deviation is the best way to demonstrate the distribution behavior of a given element in a given category. The standard deviation, albeit dependent on each analysis, is sensitive to extreme individual values. On the other hand, the mean deviation, also calculated from each value listed, is not sensitive to the extreme values. The mean deviation—the arithmetic average of the differences from the arithmetic average—is also easier to calculate than the standard deviation. For convenience and applicability to geochemical sampling problems, the mean deviation is worth consideration as a crude estimate of variability of elemental distribution in the geochemical spheres. However, the standard deviation is used in Table 2 because it is better known and can more readily be applied to statistical calculation (Shaw and Bankier, 1954). For one category—coals—the variance ratio was used, because in the paper cited the individual analyses were not published. The variance ratio (in brackets) is the maximum divided by the minimum abundance percentage.

Finally the arithmetical average is shown in boldface if the average is global or general. For these, recognized authorities were quoted. A value in parentheses indicates its value is considered questionable by the original compiler. A per cent sign applies to all values in the compartment in which the per cent sign appears.

Classification of Element Distribution

In trying to explain why elements are distributed as they are, many people have attempted classification of elements from a geochemical standpoint. Closely tied in with elemental classification is elemental mobility as a function of temperature, solubility, oxidation-reduction potential, electronegativity, lattice energy, pH, ionic radius, and other parameters tabulated as series in Table 2. One of the earliest classifications was by Vernadsky (1924). Goldschmidt (1954, p. 605) criticized his concept of dispersed elements. Since Vernadsky's attempt, interesting contributions to the problem of geochemical classification of elements have been made by Belov (1952), Kapustinskiĭ (1956), Kutina (1957), Jedwab (1953), Bokiĭ (1956), Uklonskiĭ (1949; 1953), and Tomkeieff (1954). Most of these geochemical classifications use the periodic table as a framework.

Many papers relate to the mobility of elements and associated problems of paragenesis. Korzhinskiĭ (1936; 1941; 1950; 1957), a pioneer in this field, introduced the concept of the geochemical mobility of elements. Selected aspects of this problem have been discussed by Noritomi (1953), Szádeczky-Kardoss (1953-1954), DeVore (1954), Eugster (1955), Ovchinnikov Perel'man (1956), Leutwein and Doerffel (1956, p. 92-94), D. H. Anderson and Hawkes (1958), A. P. Lebedev (1957), Lukashev (1957), and Chernoruk and Romasheva (1955).

Abundance of Elements by Category; Specific References

Selection of Abundance Data

In the selection of abundance figures for Table 2, an effort was made to obtain data from one of three types of sources. The first is a detailed analysis of many elements for a given category by a single investigator in one laboratory using the same analytical technique. The second is the screening, selection, and appraisal of abundance data of many elements by one authority in a given category from data from the literature. The following section, arranged according to category, details the references for these two types of data. The third type is the detailed investigation of many abundance categories of one element by one worker in one laboratory using a single technique. References for these data will be found in the next succeeding section, arranged according to abundance of elements by element.

Universe

The abundance data for elements in the universe are shown in two ways: parts per million

by weight including volatile elements are in bold face; number of atoms per million silicon atoms are in parentheses. All cosmic abundances in terms of atoms per million Si atoms are from Suess and Urey (1956, p. 56) with the exception of As, Ra, Ac, Th, and U. For As, respecting Ahrens' argument (Ahrens, 1956, p. 275), the maximum value of As in chondrites—4 ppm—is taken from Onishi and Sandell (1955a, p. 31). Suess and Urey's value of 4.0 atoms per million Si atoms is thus replaced by 8.1 atoms per million Si atoms or 0.0114 parts per million by weight. Cosmic abundances for Ra, Ac, Th, and U are derived from their abundance in chondrites as listed. The source of these abundances is given under the specific element in the section listing element abundances by element.

The conversion from ppm of a particular element to number of atoms per million Si atoms is

$$A = 151.8\ C/D$$

where

A = number of atoms per million silicon atoms

C = abundance in ppm of the element in chondrites

D = atomic weight of the element in question

151.8 = 100 times the quotient of 28.09/18.5 (18.5 is the average percentage of Si in chondrites (Suess and Urey, 1956, p. 59), 28.09 is the atomic weight of silicon).

All cosmic abundance data have been recalculated to parts per million (shown in boldface). The number of atoms per million Si atoms has been multiplied by the atomic weight of each element, totaled and recalculated to 100 per cent and then to parts per million. Shaw (1957, p. 168) noted that the cosmic abundance of Ga appeared low in the 1953 Geochemical Table (Green, 1953); this is because, as in this 1959 table, volatiles are calculated with nonvolatile (i.e., chondrite) abundances.

Reliability of estimates of cosmic abundance depends in part upon the theory of the origin of elements. If all the elements were created at one time, the problem is minimized. However, if elements are continually being produced in stars by nuclear processes, then representative sampling of star populations is required for nonbiased cosmic abundances. According to Dr. W. A. Fowler[2] of the California Institute of Technology, the process of element creation begins with pure hydrogen stars, which, in a series of nuclear transformations, develop a helium core. These stars then evolve into red giants. In turn, by nuclear "burning", a core of C^{12}, O^{16}, and Ne^{20} evolves within the He core. The building-up process continues with the creation of elements comprising the iron peak and virtual noncreation of Li, Be, and B. "Burning" of an iron core is energetically impossible, so the star explodes to form a nova. Recondensation and accretion of debris from such nova into new stars starts a second generation of element evolution. The elements previously formed catalyze and take part in nuclear reactions resulting in creation of all elements through bismuth. Formation of subsequent radioactive elements is achieved in supernova with the possibility that Cf^{254}, thus created, is responsible for the observed half life of such stellar events. This theory accounts for the relative cosmic absence of B, Be, and Li, the iron peak in the abundance curve, and abundance doublets in elements of atomic number greater than 50.

Meteorites

Abundances in meteorites are listed according to six possible categories: sulfide, iron, and chondrite meteorites, and sulfide, iron, and silicate phase of chondrites. The last three phases are identified by the letter *c* appearing above the average. General reviews of chondrite abundances are given by H. Brown (1949), Urey (1952b), and Vinogradov (1956). Abundances in boldface are from Vinogradov (1956) and are supplemented by specific studies for many elements noted in the section listing abundances of elements by element.

Abundances and standard deviations of the major elements in the silicate phase of chondrites are recalculated and screened from Urey and Craig (1953, p. 58, 54–55) and Wiik (1956, p. 280–281) by this author. Abundances of the alkali elements are derived from G. Edwards (1955); essentially similar results are reported in Edwards and Urey (1955). These chondrites are screened separately from carbonaceous and enstatite chondrites, which appear to be chemically distinct species. Pinson (1954) amplifies on trace-element peculiarities of carbonaceous

[2] Lecture, Origin of the Nuclear Species, May 16, 1958, at California Research Corporation, La Habra, California.

chondrites. If the six enstatite chondrites are included in the chondrite analyses of the major elements, the main difference is in silicon: Si $22.2_{1.7}$[102].

Yavnel (1955; 1957), Yavnel and Djakonova (1957), and Levin, Kozlovskaia, and Starkova (1957) include additional sets of analytical data for meteorite species. Elemental distributions and groupings in iron meteorites are detailed by Goldberg, Uchiyama, and Brown (1951), Lovering *et al.* (1957), and Nichiporuk (1958); elemental groupings in chondrites by Brown and McKinney (1957) and Lovering (1957). Certain elemental ratios in bulk chondrites are remarkably uniform—Mn/Ti = 4.07 ± 0.01; Cr/Mn = 1.03 ± 0.01; Ni/Co = 15.8 ± 0.1 (H. Brown, Personal communication).

Igneous Rocks

Four types of information are included in the section devoted to abundances in igneous rocks:

(1) General abundance figures for ultramafic, mafic, intermediate, and silicic igneous rocks, taken from Vinogradov (1956, p. 44). These are graphed as a dash in Table 2. These abundances are based on published information which is listed and evaluated by Vinogradov.

(2) Specific data for a given rock group. Hundreds of papers could have been drawn upon for information of this type. Specific ones are cited in the section detailing abundances of elements by element. In general, data by Katsura (1956) are graphed because analytical work was done systematically on an areal basis. Comparison of Katsura's work with that of Lyakhovich (1957) is instructive.

(3) Specific data for a given rock suite. This information is shown by an open triangle for a suite of extrusive rocks from Ireland (E. M. Patterson, 1951) including olivine basalt, tholeiitic basalt, quartz trachyte, and rhyolite. Again, dozens of papers could have been selected. The one chosen contains analyses involving 28 elements (Si, Al, Ti, Fe, Mg, Ca, Na, K, Be, P, Ga, Mo, Cr, V, Sn, Li, Ni, Co, Cu, Sc, Zr, Mn, Y, La, Sr, Pb, Ba, and Rb). There appears to be a regional increase in Ag, Sr, Y, Zr, and La relative to the general averages cited by Vinogradov (1956). Associated data, not cited in Table 2, appear in Patterson and Swaine (1955).

(4) Abundances in the Westerly granite (G1) and the Centerville diabase (W1), shown in black in Table 2. These are selected from a compilation with 50 references by Ahrens and Fleischer (in press). Responsibility of selection of values rests with the author, who benefited from discussion of the data with Fleischer. The original compilation should be consulted for detailed evaluation and source of the numbers.

Papers relating to the presentation and reporting of igneous-rock analyses include those by Barth (1955), Chalmers and Page (1957), Larios (1956), Whitten (1953), and Ahrens (1954c). General abundance data and principles of element distribution in igneous rocks are in Zies (1938), Borchert (1955), Ramberg (1952b), Ahrens and Gorfinkle (1950), Nockolds and Allen (1954–1956), Ringwood (1955), Nickel (1954), Förland and Weyl (1949), and Osborn (1950). Analytical compilations appear in Green and Poldervaart (1955; 1958), Nockolds (1954), Willems (1940), Zavaritsky (1954), and Taneda (1952). The compilation of igneous and metamorphic rock analyses now being prepared by Miss M. Hooker of the U. S. Geological Survey deserves special mention.

Values graphed of elements in magmatic sulfides are from a compilation in Rankama and Sahama (1950, p. 98). Wilson (1953) includes supplementary data. Many analyses of mafic intrusive and extrusive rocks appear in Wager and Mitchell (1951) and Cornwall and Rose (1957) respectively.

Abundances of elements in igneous rocks as a group are not included in Table 2 but are listed in the section detailing abundances of elements by element. The values are from Vinogradov (1956, p. 44) and are weighted two parts granite to one part basalt (*see also* Wickman, 1954, and Turekian, in press).

Metamorphic Rocks

The following elements in schist are reported in Table 2 and are identified by a superscript of 10: B, P, Si, Al, Cr, Fe, Mg, Ti, Ni, Co, Cu, V, Zr, Mn, Sc, Y, Na, Ca, Sr, Pb, K, and Ba. These values from S. R. Taylor (1955) represent schists derived from sedimentary rocks. A chemically different set of analyses of schists derived from greenstones is given in the original reference but is not included in the average. To average the two sets of data would have obscured the chemical parameters characterizing the category of schists derived from sediments. Recent general resumés of geochemical changes which accompany metamorphism are in Shaw (1954; 1956), Higazy (1952), Wenk (1954), Ramberg (1952a), Nanz (1953), and Macpherson (1958).

TABLE 1. RECORD OF CHEMICAL ANALYSES OF RUSSIAN PLATFORM SEDIMENTS

Age Divisions	#	Per Cent												Parts Per Million											
		Si	Ti	Al	Fe	Mg	Ca	Na	K	S	C (ol CO$_3$)	C (organic)		Sr	Ba	Th	U	Co	Ni	Cu				

TABLE I. RÉSUMÉ OF CHEMICAL ANALYSES OF RUSSIAN PLATFORM SEDIMENTS

Age Divisions		Per Cent											Parts Per Million						
		#	Si	Ti	Al	Fe	Mg	Ca	Na	K	S	C (of CO_2)	C (organic)	Sr	Ba	Th	U	Co	Ni	Cu
	Ls		0.90[10]	..	..	0.5[10]	12.3[18]	20.4[18]	..	..	0.02[8]	..	0.06[8]	33[8]	12[8]	..	..	..	..	..
P€	Ss	14	34.5	0.37	5.4	3.4	0.9	0.7	0.56	2.4	0.05	0.23	0.08[31]	..	..	..	..	..	..	..
	Sh	17	27.2	0.53	9.7	5.9	1.4	0.4	0.56	3.3	0.04	0.32	0.33[32]	..	..	13.7[11]	4.4[11]	20	15	48
	Ls		3.5[13]		0.7[12]	2.4[12]	7.0[16]	24.3[16]	..	..	0.13[1]	..	..	..	..	..	..	..	..	..
€	Ss	13	36.5	0.32	4.7	2.5	0.6	0.7	0.42	1.8	0.04	0.36	0.15[22]	..	..	..	..	..	..	..
	Sh	14	28.2	0.50	9.4	4.7	1.3	0.6	0.36	4.0	0.06	0.19	0.25[21]	..	..	13.2	3.7	16	25	59
	Ls		4.4[139]	..	1.6[104]	3.6[160]	5.1[401]	24.4[401]	..	..	0.10[30]	..	0.27[8]	67[6]	93[6]	4.9[6]	2.0[6]	..	..	..
O	Ss	2	24.7	0.28	5.1	4.4	2.3	7.2	0.90	1.8	0.12	2.6	0.16[14]	..	..	..	..	..	..	..
	Sh	8	20.5	0.38	6.3	3.7	2.1	9.2	0.59	3.3	0.06	3.0	1.55[7]	..	..	10.1	3.2	12	13	29
	Ls		0.90[3]	..	..	0.1[3]	4.4[18]	28.2[18]	..	..	0.40[6]	..	0.13[5]	490[4]	240[4]	4.2[4]	2.7[4]	..	..	..
S_2	Ss	1	31.1	0.09	1.0	2.5	0.7	8.9	0.46	1.1	0.02	2.6	0.11[1]	..	..	..	..	..	..	..
	Sh	6	23.2	0.36	6.7	3.8	3.0	6.4	0.51	3.7	0.06	2.0	0.23[6]	..	..	9.5	3.5	24	10	85
	Ls		9.3[18]	..	2.4[18]	2.2[18]	5.0[112]	23.1[112]	..	..	1.94[61]	..	0.23[48]	400[15]	153[15]	2.3[9]	1.2[9]	..	..	..
D_2	Ss	31	34.4	0.42	3.8	3.0	1.2	2.0	0.21	1.5	0.17	1.0	0.15[97]	..	..	..	..	..	..	..
	Sh	41	23.3	0.48	8.6	4.7	2.3	4.1	0.45	2.9	0.20	1.5	0.48[82]	..	..	10.5[19]	3.9[19]	10	15	33
	Ls		3.9[93]	..	1.9[68]	1.7[69]	2.5[534]	30.0[684]	..	..	0.21[84]	..	0.35[84]	280[27]	51[27]	3.7[21]	1.3[22]	..	..	..
D_3^1	Ss	26	36.3	0.42	4.1	3.6	0.5	0.8	0.27	1.6	0.02	0.42	0.19[104]	..	..	..	..	..	..	..
	Sh	41	21.7	0.61	7.7	4.9	1.5	7.8	0.43	2.9	0.06	2.4	0.84[101]	..	..	10.1[20]	4.4[20]	11	16	39
	Ls		5.0[21]	..	1.1[23]	0.9[20]	6.1[182]	26.5[182]	.	..	2.01[65]	..	0.23[27]	730[21]	36[21]	2.2[22]	1.3[22]	..	..	..
D_3^2	Ss	6	33.3	0.31	3.9	2.6	1.3	2.8	0.24	2.1	0.60	1.1	0.17[9]	..	..	..	..	..	..	..
	Sh	9	18.7	0.34	5.9	3.6	3.9	8.5	0.47	3.4	2.65	2.2	0.44[10]	..	..	9.9[8]	3.2[8]	13	30	49
	Ls		1.3[329]	..	0.3[316]	1.1[408]	4.6[129]	31.4[132]	..	..	0.80[556]	..	0.13[27]	403[38]	5[38]	1.3[17]	2.3[17]	..	..	..
C_1	Ss	13	35.7	0.30	3.4	2.2	0.5	2.7	0.21	0.7	0.31	0.79	0.58[29]	..	..	..	..	..	..	..
	Sh	17	25.3	0.59	9.8	4.5	0.9	2.1	0.39	2.2	0.21	0.67	1.32[28]	..	..	14.2[12]	5.9[12]	8	18	20
	Ls		2.7[108]	..	1.0[102]	0.7[27]	5.1[182]	29.8[185]	..	..	0.57[67]	..	0.11[22]	226[24]	16[24]	1.2[16]	2.7[16]	..	..	..
C_2	Ss	8	26.1	0.37	6.7	3.3	1.5	5.6	0.56	3.8	0.04	2.1	0.29[15]	..	..	..	..	..	..	..
	Sh	19	23.8	0.42	8.5	4.6	2.5	4.0	0.54	4.2	0.04	1.5	0.43[22]	..	..	12.7[13]	5.0[13]	10	38	29
C_3	Ls		3.2[97]	..	1.7[66]	0.7[65]	7.7[160]	27.3[160]	..	..	1.97[169]	..	0.16[14]	129[14]	19[14]	1.0[10]	3.4[10]	..	..	..
P_1	Ls		3.0[18]	..	0.3[3]	2.6[3]	6.6[1008]	25.2[1008]	..	..	4.21[904]	..	0.09[14]	863[17]	19[17]	1.0[9]	2.4[9]	..	..	..
	Ls		6.4[285]	..	1.6[52]	1.1[56]	4.8[148]	27.6[492]	..	..	0.72[1047]	..	0.24[4]	150[4]	67[4]	1.8[4]	5.4[4]	..	..	..
P_2	Ss	16	21.4	0.23	4.7	2.9	3.2	10.0	0.87	1.6	1.59	3.0	0.31[23]	..	..	..	..	..	..	..
	Sh	27	19.9	0.33	5.9	4.0	3.5	9.5	0.97	2.2	0.64	3.1	0.30[27]	..	..	7.7[24]	3.5[24]	9	28	30
	Ls		5.0[279]	..	1.6[101]	1.1[104]	6.1[905]	25.4[314]	..	..	3.22[808]	..	0.12[28]	790[21]	29[21]	1.3[13]	3.3[13]	..	..	..
P	Ss	16	21.4	0.23	4.7	2.9	3.2	10.0	0.87	1.6	1.59	3.0	0.31[23]	..	..	..	..	..	..	..
	Sh	28	20.1	0.34	6.1	4.0	3.4	9.2	0.96	2.2	0.62	3.1	0.30[28]	..	..	7.7[24]	3.5[24]	9	28	30
T	Ss	1	27.9	0.26	4.1	3.2	0.9	8.1	0.00	3.5	0.00	1.8	0.12[5]							

C_1	Ls		1.3^{329}	..	0.3^{316}	1.1^{466}	4.6^{1729}	31.4^{1182}	..	..	0.80^{566}	..	0.13^{37}	403^{36}	5^{36}	1.3^{17}	2.3^{17}	..	..	..
	Ss	*13*	35.7	0.30	3.4	2.2	0.5	2.7	0.21	0.7	0.31	0.79	0.58^{89}	..	..	..	..	..	..	..
	Sh	*17*	25.3	0.59	9.8	4.5	0.9	2.1	0.39	2.2	0.21	0.67	1.32^{98}	..	..	14.2^{12}	5.9^{12}	8	18	20
C_2	Ls		2.7^{606}	..	1.0^{292}	0.7^{227}	5.1^{1383}	29.8^{1435}	..	..	0.57^{407}	..	0.11^{22}	226^{24}	16^{24}	1.2^{16}	2.7^{16}	..	..	..
	Ss	*8*	26.1	0.37	6.7	3.3	1.5	5.6	0.56	3.8	0.04	2.1	0.29^{15}	..	..	..	..	..	..	..
	Sh	*19*	23.8	0.42	8.5	4.6	2.5	4.0	0.54	4.2	0.04	1.5	0.43^{22}	..	..	12.7^{13}	5.0^{13}	10	38	29
C_3	Ls		3.2^{97}	..	1.7^{66}	0.7^{65}	7.7^{259}	27.3^{960}	..	..	1.97^{769}	..	9.16^{14}	129^{14}	19^{14}	1.0^{10}	3.4^{10}	..	..	..
P_1	Ls		3.0^{48}	..	0.3^{2}	2.6^{3}	6.6^{1005}	25.2^{1005}	..	..	4.21^{934}	..	0.09^{34}	863^{37}	19^{17}	1.0^{9}	2.4^{9}	..	..	..
P_2	Ls		6.4^{285}	..	1.6^{58}	1.1^{56}	4.8^{1408}	27.6^{1492}	..	..	0.72^{1047}	..	0.24^{4}	150^{4}	67^{4}	1.8^{4}	5.4^{4}	..	..	..
	Ss	*16*	21.4	0.23	4.7	2.9	3.2	10.0	0.87	1.6	1.59	3.0	0.31^{23}	..	..	..	..	..	..	..
	Sh	*27*	19.9	0.33	5.9	4.0	3.5	9.5	0.97	2.2	0.64	3.1	0.30^{27}	..	..	7.7^{24}	3.5^{24}	9	28	30
P	Ls		5.0^{379}	..	1.6^{101}	1.1^{104}	6.1^{2005}	25.4^{2014}	..	..	3.22^{2008}	..	0.12^{18}	790^{23}	29^{23}	1.3^{13}	3.3^{13}	..	..	
	Ss	*16*	21.4	0.23	4.7	2.9	3.2	10.0	0.87	1.6	1.59	3.0	0.31^{23}	..	..	..	..	..	..	..
	Sh	*28*	20.1	0.34	6.1	4.0	3.4	9.2	0.96	2.2	0.62	3.1	0.30^{28}	..	..	7.7^{24}	3.5^{24}	9	28	30
$\overline{R}$	Ss	*1*	27.9	0.26	4.1	3.2	0.9	8.1	0.00	3.5	0.00	1.8	0.12^{5}	..	..	..	..	..	..	..
	Sh	*4*	23.7	0.43	7.8	4.3	2.2	7.2	0.76	1.9	0.04	2.0	0.05^{8}	..	..	10.0^{8}	4.1^{8}	14	36	40
J	Ls		21.8^{2}	..	4.7^{2}	8.9^{2}	1.7^{6}	18.5^{6}	..	..	0.08^{2}	..	0.26^{5}	192^{5}	86^{5}	4.7^{5}	2.3^{5}	..	..	..
	Ss	*8*	29.7	0.28	4.6	4.1	0.9	5.0	0.81	1.5	0.06	1.6	0.60^{24}	..	..	..	..	..	..	..
	Sh	*16*	25.8	0.46	8.8	4.4	1.2	3.4	1.04	2.6	0.06	1.0	1.05^{19}	..	..	14.0^{13}	3.4^{13}	11	23	34
	Ls		..	..	..	..	1.1^{1}	32.7^{1}	..	..	0.11^{1}	..	0.19^{1}	280^{1}	50^{1}	$2.0^{1?}$	$2.8^{1?}$	..	..	..

	Ls		21.8[3]	..	..	4.7[3]	8.9[3]	1.7[6]	18.5[6]	..	..	0.08[3]	..	0.26[6]	192[3]	86[3]	4.7[3]	2.3[3]	..	..	..		
J	Ss	8	29.7	0.28	4.6	4.1	0.9	5.0	0.81	1.5	0.06	1.6	0.60[24]	..	..	..	..	..	..		
	Sh	16	25.8	0.46	8.8	4.4	1.2	3.4	1.04	2.6	0.06	1.0	1.05[19]	..	..	14.0[12]	3.4[12]	11	23	34		
	Ls		..	..	..	..	1.1[1]	32.7[1]	..	..	0.11[1]	..	0.19[1]	280[1]	50[1]	2.0[1?]	2.8[1?]	..	..	..		
K_1	Ss	9	34.1	0.34	4.6	4.7	0.7	1.1	0.50	1.5	0.21	0.47	0.59[11]	..	..	..	..	..	..	..		
	Sh	8	27.2	0.52	9.9	4.6	1.2	1.2	0.99	2.2	0.10	0.26	1.26[7]	..	..	10.0<[9]	4.1<[9]	13	22	33		
	Ls		8.2[199]	..	1.3[83]	0.9[66]	0.3[172]	32.7[272]	..	..	0.10[34]	..	0.16[6]	826[6]	91[6]	2.7[3?]	1.6[3?]	..	..	..		
K_2	Ss	5	32.8	0.22	2.9	2.9	0.7	5.1	0.56	1.6	0.10	1.3	0.24[10]	..	..	..	..	..	..	..		
	Sh	4	24.1	0.30	5.6	3.2	0.9	9.6	0.85	1.6	0.00	3.1	0.54[4]	..	..	10.1<[9]	4.0<[9]	7	14	28		
	Ls		6.3[114]	..	1.1[48]	0.8[45]	0.7[148]	24.9[179]	..	..	0.08[71]	..	0.39[8]	1500[3]	220[3]	7.1[3]	3.6[3]	..	..	..		
T	Ss	3	34.9	0.31	4.2	3.0	0.8	1.9	0.50	1.4	0.15	0.45	0.40[10]	..	..	..	..	..	..	..		
	Sh	12	26.7	0.35	6.1	4.3	1.3	5.2	0.88	1.9	0.13	1.6	1.05[24]	..	..	8.6[11]	4.3[11]	8	15	28		
	Ls		1.4[15]	..	0.3[4]	0.7[7]	0.5[19]	36.0[19]	..	..	0.10[7]	..	..	..	..	..	..	..	..	..		
Q	Ss	2	32.9	0.23	3.6	2.0	1.2	5.0	0.39	2.1	0.00	1.5	0.12[8]	..	..	..	..	..	..	..		
	Sh	5	27.9	0.40	7.2	4.2	1.9	3.5	0.55	2.6	0.00	1.1	0.32[8]	..	..	11.2	4.9	6	13	17		
Over-all Average: Original Data	Ls		3.82	..	1.19	1.46	5.20	27.99	..	..	1.44	10.14	0.23	477	47	2.4	2.1	..	..	..	..	2.74%
	Ss		32.72	0.35	4.35	3.17	1.14	3.04	0.43	1.71	0.28	1.06	0.24	..	..	..	..	..	..	..	3.02%	
	Sh		23.68	0.47	7.99	4.53	2.00	5.14	0.60	2.90	0.25	1.66	0.67	..	..	11.0	4.1	11	22	35	5.58%	

Except for organic carbon, data are abstracted and recalculated to ionic-weight percentages from Vinogradov, Ronov, and Ratynskii (1952), Vinogradov and Ronov (1956a; 1956b), and Baranov, Ronov, and Kunashova (1956). Values for organic carbon in sediments are taken from Ronov (1958, p. 411). Katchenkov (1956) details the distribution of some of these elements (Na, Mg, Sr, Ba, Ni, and Cu) as well as Mn, V, and Cr for 279 clay samples in 17 time divisions in Paleozoic clays of the Ural-Volga region.

Details of age designations with original-age designation symbol in parentheses as follows: (Sn_2)—P€, upper Proterozoic, Rhipheus (blue); (Cm)—€, Cambrian; (S_1)—O, Ordovician; (S_2)—S_2, upper Silurian, Gothlandian; (D_2)—D_2, middle Devonian; (D_3^1)—D_3^1, upper Devonian, Frankian stage; (D_3^2)—D_3^2, upper Devonian, Famennian stage; (C_1)—C_1, lower Carboniferous; (C_2)—C_2, middle Carboniferous; (C_3)—C_3, upper Carboniferous; (P_1)—P_1, lower Permian; (P_2)—P_2, upper Permian; (T)—$\overline{T}$, Triassic; (J)—J, Jurassic; (Cr_1)—K_1, lower Cretaceous; (Cr_2)—K_2, upper Cretaceous; (Tr)—T, Tertiary; (Q)—Q, Quaternary.

The symbol # refers to number of composite analyses for sandstones and shales. For Si, Al, and Fe in carbonates the superscript indicates the number of individual analyses; for Mg, Ca, and S in carbonates the superscript indicates the sum of composite and individual analyses in the two sets of data reported by Vinogradov and Ronov (1956a, p. 4-5); for other elements in carbonates the superscript refers to the number of composite analyses involved. The original references should be consulted for data regarding the number of samples involved in the composites. The corrected value of SiO_2 in Tertiary shales appearing in Vinogradov and Ronov (1956b, p. 6) was used. Enclosed averages are not used in the calculation of the over-all average listed in Table 2 because the number of individual analyses was deemed too small or because the data can be obtained from consideration of other values cited for the same geologic period. One average (0.02 per cent S based on 2 individual analyses) of the two sets of data for S in Jurassic carbonates was discarded; the other (0.08 per cent S based on 2 composites of 25 samples) was retained. Also, according to Vinogradov and Ronov (1956a, p. 8), the data for sandstones are preliminary; the study is still in progress.

The over-all averages are taken from Vinogradov and Ronov (1956a, p. 11). Regarding carbonate rocks, Ti, Na, and K were not determined. Values for these elements in Paleozoic carbonates in Illinois, screened and recalculated from Lamar (1957), are as follows (superscript indicates number of individual analyses and subscript the standard deviation):

Ti $0.05_{9\cdot0}{}^{37}$ (discarding one analysis: La7 TiO_2 1.03 per cent, SiO_2 33.58 per cent)
Na $0.07_{0\cdot68}{}^{87}$ (discarding one analysis: NF96 Na_2O 2.32 per cent, no K_2O reported)
K $0.22_{0\cdot22}{}^{90}$ (discarding one 1907 analysis: K_2O 2.94 per cent, Al_2O_3 5.63 per cent)

For the over-all Russian carbonate average, the data include results of between 1242 and 8351 individual analyses averaged in with 198 composite analyses involving 8847 samples. Regarding sandstones, the 158 composite analyses represent 3709 samples. For shales, the 252 composite analyses involve 6804 samples. In both cases the loss on ignition includes organic matter, water of crystallization and constitution, haloids, and sulfide sulfur. The over-all average for Th and U in carbonates and shales is taken from Baranov, Ronov, and Kunashova (1956, p. 6). In carbonates the average is based on 128 composites representing 5475 samples; in shales the average is based on 178 composite analyses representing 4795 samples. For organic carbon in sediments, the over-all average for shales is based on 418 composite analyses involving 9217 samples, for sandstones on 402 composites of 6184 samples, and for carbonates on 285 composites based on 10341 samples.

Deep-Sea Sediments

There are many excellent sets of analyses of pelagic sediments; those of Berrit and Rotschi (1957) are noteworthy. Trask's (1955, p. xl–lvi) review of progress in studies of recent marine sediments from 1949 to 1954 cites many sources of analytical data. The "red clay" analyses chosen for the suite noted by the superscript 17 are from Goldberg and Arrhenius (1958, p. 170–171). Calcareous and diatomaceous cores have been screened from the analyses cited, *i.e.*, Cap 32HG, Cap 33HG, NH9, Ck 8 and Ck 9. The elements involved are Si, Al, Fe, Ti, Mg, Ca, Na, K, Sr, Ba, B, Mn, Ga, Ni, Cu, Co, Cr, V, Pb, Li, Be, Mo, Zr, Yb, Y, La, and Sc. Turekian (in press) gives a critical evaluation of elemental abundances (64 elements) in pelagic carbonate cores. Source data of pelagic abundances of elements not listed heretofore are in the section which lists element abundances by element.

Attention is also called to papers by Revelle *et al.* (1955), Romm (1956a; 1956b), E. J. Young (1954), Krauskopf (1955b), Hamaguchi *et al.* (1958) and P. J. Wangersky (1958, unpub. PhD thesis, Yale Univ.).

Shales, Sandstones, and Carbonates

There are two main sources of information for these rock types. One bank of data (in boldface) is for the elements indicated in the categories:

Shales, sandstones, and limestones—Si, Al, Fe, Mg, Ca, organic C and S

Sandstones and shales—Si, Al, Fe, Mg, Ca, organic C, and S, *plus* Ti, Na, K, and C (of CO_2

Limestones—Si, Al, Fe, Mg, Ca, organic C, and S, *plus* Sr and B

Shales—Si, Al, Fe, Mg, Ca, organic C, and S, *plus* Th, U, Co, and Ni

The numbers are further identified by both superscript and subscript in parentheses. These numbers are compiled from the Russian literature and are recomputed to ionic-weight percentages as shown in Table 1. The superscripts in Table 1 indicate the number of individual analyses. In the original data, the averages are computed on the basis of number of analyses. The original over-all averages are given in Table 1. In Table 2, the averages are computed giving each geologic time division shown in Table 1 equal weight. Thus, for these boldface numbers of elemental abundances in sediments of the Russian Platform, the superscript is not the number of individual analyses but the number of time divisions used in calculation of the average and standard deviation. Thus the standard deviation for this suite of data should not be compared with other standard deviations of averages of these rock types.

The other bank of data, from Ostrom (1957), is for Paleozoic shales and carbonates of Illinois, identified by superscripts of 17 and 91 respectively. The elements involved are: B, Ba, Cr, Cu, Fe, K, Mn, Mo, Na, Ni, Pb, Sr, Ti, V, and Zn. Only one value is omitted from Table 2 of the Illinois set of abundances—that of Mo in shales of 7_{14}^{17} ppm.

In many cases, pre-1950 abundances for the rare metals are used in the shale, sandstone, and carbonate categories. The writer has used Krauskopf's (1955a) values; Krauskopf has cited the sources evaluated. Not all Krauskopf's values are used (*see* specific element entries for references).

Finally, sources of analytical data not used in Tables 1 or 2 include Barnes (1957), Tourtelot (1957), Spiro, Gramberg, and Vovk (1956), and Ronov and Khlebnikova (1957). Principles of element distribution in sediments are given by Wickman (1944), Strakhov, Salmanson, and Glagoleva (1956), Tikhomirova (1957), Katchenkov (1956), Katchenkov and Flegontova (1955; 1958), and Krumbeim and Garrels (1952), with general compositional resumés by Sujkowski (1952) and Poldervaart (1955). A comprehensive compilation of sedimentary rock analyses is being prepared by W. W. Rubey of the U. S. Geological Survey.

Marine Hydrosphere

Dr. E. D. Goldberg of Scripps Institution of Oceanography kindly supplied the abundance values for the marine hydrosphere shown in boldface. The source of the abundance data shown in lightface (Sr, Ga, and Ge) is given in the section on element abundances by element. The author reviewed the literature data compiled by Dr. Goldberg and was informed of the reasons for the numbers selected. Some elements, such as silicon, calcium, phosphorus, and carbon, are subject to wide variation both areally and vertically, because of biologic activity. The following recent references treat this problem fully: Goldberg (1954), Harvey (1945; 1955), Hutchinson (1947), Krauskopf (1955b; 1956), and Richards (1956; 1957). Some aspects of the geochemistry of pelagic sedimentation as a function of climate are

covered by Broecker, Turekian, and Heezen (1958).

The transfer percentage is calculated from (1) the oceanic abundance values appearing in Table 2, and (2) the abundance values for the average igneous rock. The latter, weighted two parts granite to one part basalt, is listed in the alphabetical arrangement of elements appearing in the section Abundance of Elements by Element. The transfer percentage is based on the assumption that for every kilogram of ocean water, 600 grams of igneous rock have been weathered. Goldschmidt (1954, p. 57), and Correns (*in* Houtermans and Jordan, 1946, p. 127) concur on the magnitude of this number; Rankama (1954b) does not.

Weathered and Leached Rocks

No data on weathered or leached rocks and soils are included in Table 2. The average value of any particular element in soils is questionable because of the diverse nature of soils. However, under the alphabetical listing of elements, an average value is cited from Vinogradov (1954b, p. 214–215). This book and also Vinogradov (1957) and Swaine (1955) should be consulted for analytical data of elemental distributions in soils of different origins and areas.

Niggli's (1952, p. 11–96) chapter on weathering studies (with bibliography) is probably among the best treatments of the subject and might be supplemented by Krotov (1953), McLaughlin (1955), Yamasaki, Iida, and Yokoi (1955), Butler (1953; 1954), Vendl (1957), and Lukashev (1958).

Studies on leached materials in rocks are more rare. The work by Spiro, Gramberg, and Vovk (1956, p. 90–93) deserves wider circulation in translation. Brown *et al.* (1954a; 1954b) treat the problem differently and with different rock types.

Nonmarine Hydrosphere

As in the case for soils, abundance values for nonmarine waters depend strongly on the source of water involved and the nature of terrain or lithology traversed. Analytical data appear in many diverse publications, including O. Arrhenius (1954), G. E. Hutchinson (1957), Hawkes (1957, p. 228–229), Chebotarev (1955), Herman (1956), Meents *et al.* (1952), Schoeller (1956), Spiro, Gramberg, and Vovk (1956), Valyashko (1954), White (1957a; 1957b) and Zyka (1957). The bibliographies of these papers are extensive. Craig, Boato, and White (1956) discuss the isotopic geochemistry of thermal waters. Table 2 does not cite nonmarine hydrosphere abundances.

Other Geochemical Spheres

Abundances of elements in the atmosphere, not listed in Table 2, are covered by Kuiper (1952), Rankama (1954c), Damon and Kulp (1958), Borst (1953), Adams and Pliler (1956), and Asimov (1955).

For abundances of elements in coal and coal ash, two major sources of information are quoted. The analytical data of Headlee and Hunter (1955, p. 549) include abundances of 38 elements in coal ash from 16 coal seams in West Virginia with a total of 596 spot analyses. These elements are Li, Na, K, Rb, Ca, Sr, Ba, Mg, Al, Si, Fe, Ti, Ag, As, Be, Bi, B, Cr, Co, Cu, Ga, Ge, Hg, La, Mn, Mo, Ni, P, Pb, Sb, Sn, V, W, Zn, Zr, Cd, Ce, and Te. The abundance value for O was calculated by the compiler. Some of the rare earth elements (exclusive of La), Cs, Os, Au, U, Pt, and Tl, were sought but not found. Because of the dependence of sulfur content on temperature of ashing and calcium content, all the data are given on a sulfur-free basis. Details of averaging the cube and column analyses may be found in the original reference. The variance ratio—the maximum value obtained divided by the minimum value—is derived from individual cube analyses, not composited column averages. This suite of samples is identified by a superscript of 596. Values for Au, Cd, In, Sc, and Tl in coal ash are from Krauskopf (1955a). For other elements in coal and coal ash, see the specific element listing (*see also* Selvig and Gibson, 1956, and Stadnichenko *et al.*, 1953).

Many analytical data on Hungarian bauxites are interpreted by Bárdossy (1958); data on Arkansas bauxites are interpreted by Gordon and Murata (1952).

Elemental abundances in rock salt for a few elements are taken from Thompson and Wardle (1954, p. 177) and are so indicated under the specific element listing. Data for K, Pb, Ca, Mg, Sr, Si, Rb, Mn, Ag, and Al are not included in Table 2. As, Au, Ba, Be, Bi, Cd, Co, Cr, Ga, Ge, Hg, In, Li, Mo, Sb, Tl, W, Zn, and Zr are listed as "not detected" in rock salt by Thompson and Wardle (1954). However, abundances of some of these elements in halite are obtained from other sources. (*See* Lotze, 1957, and Kashkarov, 1956.)

Another bank of data not in Table 2 is

abundance of elements in marine organisms; the reader is referred to Vinogradov's (1953) monograph in English translation, particularly the chapter on changes in the elemental composition of marine organisms during geologic time (p. 576–586).

Abundances in crude oils are noted under the specific element. A detailed study of one area on distributions of vanadium, nickel, and copper in specific age groups is given by Witherspoon and Nagashima (1957). Petrova and Karpova (1954), McKinney and Garton (1957), and Katchenkov and Flegontova (1955) supply additional analytical data. Zyka's (1958) article on the chemistry of oil-field waters strengthens the arguments of Hodgson and Baker (1959) on the geochemical aspects of petroleum migration.

Minerals

Source data for abundances of elements in nonsilicate minerals are derived primarily from Palache, Berman, and Frondel (1944; 1951). A standard procedure was adopted for processing the mineral analyses cited therein. The idealized mineral analysis was used where no other analytical data were cited. Where analyses were cited, the idealized mineral analysis was rejected in computation of the standard deviation and average. Of the remaining analyses, only individual analyses were used. In mineral groups, such as the apatites, the particular species is indicated where warranted. For some minerals, specifically the silicates, reference is made to papers noted in the alphabetical listing of elements.

Abundance of Elements By Element; Detailed References and Isotope Bibliography

This listing does not repeat specific element suites selected for categories previously discussed. These suites include the cosmos, chondrites, igneous rocks, schists, deep-sea sediments, magmatic sulfides, shales, sandstones, carbonates, cherts, coals, and ocean waters. In some categories, such as in shales, carbonates, and chondrites, two sets of data overlap. In such cases if one set of data is obtained from the Russian literature, it is identified either by boldface or by superscripts and subscripts in parentheses. The following listing clarifies other situations where more than one value appears in any given category. This listing includes abundances of elements in parts per million in soils and igneous rocks taken from Vinogradov (1954b, p. 214–215; 1956, p. 44–45). The abundances in igneous rocks (weighted two parts granite to one part basalt) are used in the calculation of transfer percentages in ocean waters. Other than identifying numbers used in Table 2, no attempt is made to make this listing complete or comprehensive. However, interesting or pertinent papers or categories, the data of which are not included in the Table, are identified by an asterisk. The bibliography of nonradiogenic isotopes is exclusive of papers dealing with instrumentation or methodology. Atomic numbers appear beside the element name.

Actinium (89)

Soils*—(no data) Igneous rocks*—5.5×10^{-10}

General*—Adams and Pliler (1956)

Aluminum (13)

Soils*—71300 Igneous rocks*—81000

Metal phase of meteorites—compilation by H. Brown (1949, p. 626)

Limestone—Lamar (1957)*

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)

Deep-sea sediments—G. E. Hutchinson (1943)*

Isotopes*—Ehman and Kohman (1958)

Antimony (51)

Soils*—(no data) Igneous rocks*—0.3

Iron and silicate phase of meteorites, iron phase of chondrites—Onishi and Sandell (1955b). Where two or three values were given for one sample, they were averaged for computation of the over-all average and standard deviation.

Sulfide phase of meteorites—Noddack and Noddack (1930). Their value of 7.8 is rounded to 8.

Deep-sea sediments, shales, sandstones, carbonates, and slate—Onishi and Sandell (1955b)

Asphalt and petroleum ash—maximum of 200? ppm in compilation by Krauskopf (1955a, p. 419)*

Argon (18)

Soils*—(no data) Igneous rocks*—0.04

Iron meteorites—Genther and Zähringer (1955); Gerling (1956)*; Vinogradov, Zadorozhny and Florenskiĭ (1957)*

Silicate phase of meteorites—the Nuevo Laredo achondrite, Reynolds and Lipson (1957)

Igneous rocks—estimated 2.2×10^{-5} cc/gm, Turekian (in press)*

Atmosphere*—Polanski (1957); Damon and Kulp (1958)

Isotopes* (including some radiogenic isotopes)—

Herzog *et al.* (1955); Nier (1950); Sardarov (1957); Fleming and Thode (1953); Boato, Careri, and Santangelo (1952); Geiss and Hess (1958); Fireman (1958)

Arsenic (33)

Soils*—5 Igneous rocks*—2

Atomic radius—Tobelko, Zvonkova, and Zhdanov (1954)*

Iron and silicate phases of meteorites; iron, sulfide, and silicate phase of chondrites—Onishi and Sandell (1955a)

Sulfide phase of meteorites—Noddack and Noddack (1930)

Slate, quartzite, deep-sea sediments, shales, graywackes, sandstones, dolomites, and limestones—Onishi and Sandell (1955a)

Chert—(J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)

Asphalt and petroleum ash—Average of 1500 ? in compilation by Krauskopf (1955a, p. 419)*

Barium (56)

Soils*—500 Igneous rocks*—640

Chondrites—Pinson, Ahrens, and Franck (1953, p. 253), superscript of 20 (one analysis, Long Island, discarded because of its excessively high value—the original authors also omitted it from their mean); Hamaguchi, Reed, and Turkevich (1957), superscript of 4.

Ultramafic rocks—Pinson, Ahrens, and Franck (1953)

Granite—Cocco (1953)*

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)

Asphalt and petroleum ash—Average of 500–1000 ppm in compilation by Krauskopf (1955a, p. 419)*

General*—Heide and Christ (1953), Shaw (1957b)

Isotopes*—Sampson and Bleakney (1936)

Beryllium (4)

Soils*—(~1) Igneous rocks*—4.2

Chondrites—Urey (1952, p. 252)

Igneous rocks—Sandell (1952); Beus and Sazhina (1956)*; R. Kuroda (1956)*

Shales, including some phosphates and coals (40 localities), sandstones (10 localities), limestones (3 localities), regional metamorphic rocks (no subscript, 10 localities), and pyrometasomatic deposits, abbreviated "pyro" (120 localities), residual bauxite and manganese, and beryl—Warner *et al.* (in press). The abundance of Be in New Zealand schists (S. R. Taylor, 1955, p. 187) is equal to or less than 1 ppm

Deep-sea sediments—Tatsumoto (1956–1957, Part XXVI)*

Quartzite—Rankama and Sahama (1950, p. 447)

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)*, <0.1–1 ppm Be, semiquantitative

Asphalt and petroleum ash—average of 2? in compilation by Krauskopf (1955a, p. 419)*

Coal—Rouir (1954)*

General*—Beus (1956a; 1956b); Merril, Honda, and Arnold (1958)

Isotopes*—Goel *et al.* (1957); Arnold (1954, *cited in* Lopez de Azcona, 1955, p. 196); Arnold and Al-Salih (1955); Thor and Zutshi (1958); Ehmann and Kohman (1958); Merril, Honda, and Arnold (1958)

Bismuth (83)

Soils*—(no data) Igneous rocks*—(~0.1)

Iron phase of meteorites—compilation by H. Brown (1949, p. 626)

Silicate phase of meteorites—Rankama and Sahama (1950, p. 738) (See note following section on Abundances.)

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)

Sandstone and shale—compilation by Krauskopf (1955a, p. 419)

Isotopes*—Riezler and Porschen (1952); Peppard *et al.* (1952)

Boron (5)

Soils*—10 Igneous rocks*—13

Igneous rocks—Tageeva (1943)*; granite, Wasserstein (1951)*; volcanic rocks, Kawaguchi (1958)*

Sediments—marine sediments, Landergren (1945, 1958)*; limestones, Heide and Thiele (1958).* Pure or nearly pure shell limestones from Steudnitz near Jena contain 2.8–49.9 ppm B with an average of 15.4 ppm B. The average for all limestones is taken at 10 ppm B by Heide and Thiele (1958). Their range for argillaceous rocks from Göschwitz near Jena is 54.1 to 111.1 with an average of 81.8 ppm B; the average for all shales is taken at 79 ppm B. *See also* Tamrazyan (1957).*

Quartzite—compilation by Rankama and Sahama (1950, p. 491)

Sea water—Ponizovskiĭ and Meleshko (1957)*

Isotopes*—Thode *et al.* (1948); Parwel, Ubisch, and Wickman (1956)

Bromine (35)

Soils*—(no data) Igneous rocks*—1.8

Iron and silicate phase of meteorites—compilation by H. Brown (1949, p. 626)

Igneous rocks, deep-sea sediments, shales, sandstones, graywackes, limestones, dolomites, coal, hydrocarbons, marl, and novaculite—Behne (1953)

Evaporites—Itkina (1956)*; Valyashko (1956)* The wide range of Br in halite (50–600 ppm) has environmental significance; Lang (1954)* obtains 200–300 ppm in halite.

Isotopes*—Robinson and Briscoe (1925); Cameron (1953)

Cadmium (48)

Soils*—(0.5) Igneous rocks*—0.13

Sulfide and iron phase of meteorites—compilation by H. Brown (1949, p. 626)

Chondrites—Onishi and Sandell (1957, p. 268) (calculated)

Shale and coal ash—compilation by Krauskopf (1955a, p. 416 and 418 respectively)

Sea water—Mullin and Riley (1958)

Calcium (20)

Soils*—13700 Igneous rocks*—33000

Silicate phase of chondrites—recomputed from Urey and Craig (1953) and Wiik (1956) by this author

Iron phase of meteorites—compilation by H. Brown (1949, p. 636)

Igneous rocks—Gerasimovskiĭ and Lebedev (1958)*

Limestones—Lamar (1957)*

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota). Samples 10 and 23 are relatively high in carbonate.

Isotopes*—Pinson *et al.* (1957); Herzog *et al.* 1955); Hurley (1958)

Carbon (12)

Soils*—20000 Igneous rocks*—230

Iron phase of meteorites—compilation by H. Brown (1949, p. 626)

Igneous rocks—A. P. Lebedev (1957)*

Deep-sea sediments—Zaitseva (1956), organic C, superscript of 7 (3 stations in Pacific); other values from F. W. Clarke (1924) and Bader (1955)

Recent marine (organic)—Bader (1955), superscript of 34

Shale—carbonate and organic carbon (Ronov, 1958). *See* Table 1.

Sandstone and limestone—carbonate and organic carbon (Ronov, 1958). *See* Table 1. *See also* Trask and Patnode (1952, p. 30)*, organic carbon

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)*, 0.00–0.33 per cent. Samples 10 and 23 are relatively high in carbonates.

Sediments, organic carbon—Strakhov and Rodionova (1954)*; Rooney (1956)*; Ilchenko and Mendes (1957)*

General*—Borchert (1951)

Isotopes*—Attree *et al.* (1954); Baertschi (1951; 1952; 1953a; 1957); Boato (1954a); Craig (1951; 1954a; 1954b; 1954c; 1957a; 1957b; Currie (1951); Dansgaard (1953b); Eckermann, Ubisch, and Wickman (1952); Engel, Clayton, and Epstein (1958); Fabian (1955); Gavelin (1957), Geijer (1956), Haul (1954); Holmes (1956); Jeffery *et al.* (1955); Keeling (1958); Kerwin, McElcheran, and Cottin (1957); Korff (1954); Landergren (1953; 1954; 1955; 1956; 1957); Mars (1951); Naughton and Terada (1954); Nier (1950); A. L. Promislow (1955, unpub. PhD thesis, Univ. Illinois); Rankama (1948; 1954c–1954h); Rooney (1956); Schajn and Hase (1952; 1954); Schopp (1954); Silverman and Epstein (1958); E. W. Taylor (1955, unpub. MS thesis, McMaster Univ.); Trofimov (1949b; 1950; 1952); Tunitsky, *et al.* (1957); Wickman (1952; 1953; 1956); Wickman and Ubisch (1951)

Cerium (58)

Soils*—(50) Igneous rocks*—(40)

Minerals—Murata, Rose, and Carron (1953)*; Murata, Rose, Carron, and Glass (1957)*

Isotopes*—Ce^{142}, Riezler and Kauw (1957)

General*—rare-earth elements, Masuda (1957)

Cesium (55)

Soils*—(5) Igneous rocks*—(10)

Chondrites—Cabell and Smales (1957, p. 404)*; Gordon, Friedman, and Edwards (1957)*; Webster, Morgan, and Smales (1958, p. 151), superscript of 12

Sulfide phase of meteorites—Noddack and Noddack (1930)

Igneous rocks—analytical, Liebenberg (1956)*; granite, Deleon and Ahrens (1957)

Deep-sea sediments (red clay), shales (superscript of 26), sandstones, limestones (superscript of 7), near-shore sediments (7_3^{10} ppm Cs) and hornfels—Horstman (1957). Other shale value from Canney (1952)

Minerals (lepidolite and beryl)—Cabell and Smales (1957, p. 401–402 respectively)

Isotopes*—Tomlinson, Fleming, and Thode (1954)

Chlorine (17)

Soils*—100 Igneous rocks*—230

Iron and silicate meteorite (Mocs)—compilation by Correns (1956, p. 183)

Igneous rocks—Kuroda and Sandell (1953)*; Iwasaki *et al.* (1957)*

Igneous rocks, deep-sea sediments, shales, sandstones, graywackes, limestones, dolomites, novaculites, and hydrocarbons—Behne (1953)

Coal—compilation by Correns (1956, p. 208)

Isotopes—Davis and Schaeffer (1955)*; Half life of Cl^{36}—Schaeffer and Davis (1956); Kuroda *et al.* (1957)*; Harkins and Stone (1926)*

Chromium (24)

Soils*—200 Igneous rocks*—117

Sulfide phase of meteorites—compilation by H. Brown (1949, p. 626)

Iron meteorites and stony iron meteorites (superscripts of 89 and 9 respectively)—Lovering *et al.* (1957, p. 270–272); Henbury and Perryville analyses discarded—*see* Lovering *et al.*, p. 267. Tucson analysis discarded—excessively high value. If Tucson is retained the average is 73_{252}^{90}. *See also* Nichiporuk (1958)

Silicate phase of chondrites—recomputed from Urey and Craig (1953) and Wiik (1956) by this author

Igneous rocks—Turekian (1956), numerical value noted for basalts. *See also* Fairbairn, Ahrens, and Gorfinkle (1953)* for abundance in diabase. Volcanic rocks, Ishimori (1950)

Sandstone—compilation by Krauskopf (1955a, p. 416)

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)

Asphalt and petroleum ash—average of 200–3000 ppm in compilation by Krauskopf (1955a, p. 419)*

Isotopes*—Hess and Inghram (1949)

Cobalt (27)

Soils*—8 Igneous rocks*—18

Sulfide phase of meteorites—compilation by H. Brown (1949, p. 626)

Iron meteorites—superscript of 31, Goldberg, Uchiyama, and Brown (1951, p. 16–17)

Stony iron meteorites—superscript of 9, Lovering *et al.* (1957, p. 272); *see also* Nichiporuk (1958)*

Igneous rocks—diabase, Fairbairn, Ahrens, and Gorfinkle (1953); volcanic rocks, Katsura (1956, Parts XXXVIII, XXXIX); norite, Stonehouse (1954)*; basalts, Turekian (1956), numerical value indicated; Vekilova (1958)*

Deep-sea sediments—Tatsumoto (1956–1957)*; Hutchinson *et al.* (1955)*

Recent marine sediments—R. S. Young (1957)*

Sandstones, carbonates, and asphalt and petroleum ash—compilation by Krauskopf (1955a, p. 416, 416, and 419 respectively)

Isotopes*—Ehmann and Kohman (1958)

General*—M. H. Carr and K. K. Turekian (1959, unpub. paper, *A preliminary report on the geochemistry of cobalt*, presented at 40th annual meeting, Am. Geophys. Union, Washington, D.C., May 5, 1959)

Copper (29)

Soils*—20 Igneous rocks*—70

Iron meteorites and stony iron meteorites (superscripts of 89 and 9 respectively)—Lovering *et al.* (1957, p. 270–272); Henbury and Perryville analyses discarded—*see* note in Lovering *et al.*, p. 267; Nichiporuk (1958)*

Chondrites—Onishi and Sandell (1957, p. 268)

Igneous rocks—basalts (numerical value indicated), Turekian (1956); diabase, Fairbairn, Ahrens, and Gorfinkle (1953)*; volcanic rocks, Katsura (1956, Part XL); granite, R. Kuroda (1956—1957, Part VI)*

Deep-sea sediments—Tatsumoto (1956–1957, Parts XXIV, XXV); G. E. Hutchinson *et al.* (1955)*

Continental sediments—Abramovich (1957a)*

Sandstone—compilation by Krauskopf (1955a, p. 419)

Chert—J. A. Maxwell (1953, unpublished PhD thesis, Univ. Minnesota)* <1–100 ppm, semi-quantitative

Rock salt—Thompson and Wardle (1954, p. 177)

Hydrocarbons—Hyden (1955); Nagashima and Machin (1957)*

Asphalt and petroleum ash—average of 200–8000 ppm in compilation by Krauskopf (1955a, p. 419)

General*—Morita (1954)

Isotopes*—Brown and Inghram (1947); Walker, Cuttitta, and Senftle (1958)

Dysprosium (66)

Soils*—(no data) Igneous rocks*—(4)

Erbium (68)

Soils*—(no data) Igneous rocks*—(2)

Europium (63)

Soils*—(no data) Igneous rocks*—(~1)

General*—Fenoglio and Rigault (1957)

Fluorine (9)

Soils*—200 Igneous rocks*—660

Atomic weight—Scott and Ware (1957)*

Chondrites—Urey (1952, p. 252)

Igneous rocks, schists, welded tuffs, shales (superscript of 7), sandstones, limestones, and coal exclusive of analyses numbers 282, 283, 287–291 (superscript of 16)—Kokubu (1956). Because interlaboratory standards were used, Kokubu's work may be compared with that of R. H. Seraphim (1951, unpub. PhD thesis, Mass. Inst. Technology)* and Koritnig (1951)*; *see also* Danilova (1949)*; Tageeva (1943)*; Borchert (1952)*

Pelagic sediments—R. H. Seraphim (1951, unpub. PhD thesis Mass. Inst. Technology)*, 3 Atlantic cores: $910_{430}{}^{48}$ ppm F

Minerals—fluorine substitution, Valkenburg, Weir, and Bunting (1957)*

Gadolinium (64)

Soils*—(no data) Igneous rocks*—(7)

Gallium (31)

Soils*—(~10) Igneous rocks*—26

Iron meteorites—superscript of 45, Goldberg, Uchiyama, and Brown (1951, p. 16–17)

Stony iron meteorites—superscript of 9, Lovering *et al.* (1957, p. 272); Nichiporuk (1958)*

Chondrites and sulfide, iron, and silicate phase of chondrites (the last three phases with a superscript of 3)—Onishi and Sandell (1956, p. 80)

Igneous rocks—Sandell (1949)*; norite, Stonehouse (1954)*; diabase, Fairbairn, Ahrens, and

Gorfinkle (1953); Walenczak and Pendias (1958)*
Schist (includes shales, schists, and gneiss)—Shaw (1957, p. 186)
Sandstones, carbonates, and asphalt and petroleum ash—compilation by Krauskopf (1955a, p. 416, 416, and 419 respectively)
Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)* not detected—1 ppm
Minerals—sphalerite, Morris and Brewer (1954, p. 138); germanite, Goldschmidt (1954, p. 329); Vorob'ev (1957)*
Sea water—Culkin and Riley (1958)
General*—Shaw (1957a); C. K. Bell (1955); Nishikawa (1958); Borisenko (1959)
Isotopes*—Inghram *et al.* (1948); Sampson and Bleakney (1936)

Germanium (32)

Soils*—(~1) Igneous rocks*—2
Iron meteorites—superscript of 90, Lovering *et al.* (1957, p. 270–271); Henbury and Perryville analyses discarded—*see* note in Lovering *et al.*, p. 267; Nichiporuk (1958)*; Wardani (1956; 1957)
Stony iron meteorites—superscript of 9, Lovering *et al.* (1957, p. 272)
Igneous rocks—Wardani (1957, p. 13); value for intermediate rocks coincides with Vinogradov's 1956) data; Harris (1954)*
Deep-sea sediments—Wardani (1957, p. 15*; 1958, p. 252), superscript of 27 for north Pacific Ocean pelagic sediments, 4 for south Pacific pelagic sediments
Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)
Coal—Fortescue (1954)*; Szádeczky-Kardoss and Benko (1956)*; Breger and Schopf (1955)* their data give $470_{220}{}^{4}$ ppm Ge), Schleicher and Hambleton (1954)*; Rouir (1954)*
Asphalt and petroleum ash—maximum of 200 ppm in compilation by Krauskopf (1955a, p. 419)*
Minerals—sphalerite, Brewer, Cox, and Morris 1955, p. 133)
Sea water—Burton and Riley (1958)*; Wardani 1958, p. 239)
General*—Cipriani (1954); Wardani (1957); Onishi (1956); Frondel and Ito (1957); Shaw (1957)
Isotopes*—Reynolds (1953a); Ordzhanikidze and Zabareva (1957); Graham *et al.* (1951)

Gold (79)

Soils*—(no data) Igneous rocks—(~0.001)
Iron meteorites—superscript of 45, Goldberg, Uchiyama, and Brown (1951, p. 16–17)
Igneous rocks—Vincent and Smales (1956)*; Crocket, Vincent, and Wager (1958)*
Sandstones and carbonates—compilation by Krauskopf (1955a, p. 416). Average of carbonate values taken.
Black shale and coal ash—compilation by Krauskopf (1955a, p. 417 and 418 respectively)

Hafnium (72)

Soils*—(no data) Igneous rocks*—(3)
Igneous rocks—An abundance of around 1 ppm Hf in igneous rocks is indicated by Gottfried, Waring, and Worthing (1956)*
General*—Pácal (1957b); Lejeune (1954)
Isotopes*—Reynolds (1953a)

Helium (2)

Soil*—(no data) Igneous rocks*—?
Iron meteorites—Chackett, Reasbeck, and Wilson (1953, p. 269); Fireman and Schwarzer (1957)*; Genther and Zahringer (1955)*; Gerling (1956)*; Vinogradov, Zadorozhnyĭ, and Florenskiĭ (1957)*
Stony meteorites—Reynolds and Lipson (1957); Paneth, Reasbeck, and Mayne (1952); Mayne (1956)*; Chackett *et al.* (1951)*; Cherdyntsev and Abdulgafarov (1956)*
Igneous rocks—estimated 6×10^{-5} cc/gm, Turekian (in press)*
Sediments—Mayne (1956; 1957a)*; Damon (1957)*; Aldrich and Nier (1948)*
Rock salt—Thompson and Wardle (1954, p. 177)
Atmosphere*—Damon and Kulp (1958); Borst (1953)
Natural gas*—Faul *et al.* (1954); Anderson and Hinson (1951); Anonymous (1954)
General*—Szelényi (1941)
Isotopes*—Coon (1949); Nier (1956); Menke (1953); Geiss, Oeschger, and Signer (1958)

Holmium (67)

Soils*—(no data) Igneous rocks*—?

Hydrogen (1)

Soils*—(no data) Igneous rocks*—?
Chondrites—compilation by H. Brown (1949, p. 646)
Igneous rocks—(in H_2O^+ only) Nockolds (1954)
Sediments—(in H_2O^+ only) Yoder (1955)
Chert—(in H_2O^+ only) J. A. Maxwell (1953, Unpub. PhD thesis, Univ. Minnesota)
General*—Edelman (1948)
Isotopes*—Baertschi (1953b); Bertram and Mendel (1936); Boato (1953; 1954a; 1954b; 1956); Bokhoven and Theeuwen (1956); Clarke, Denton, and Reynolds (1954); Czike and Fodor-Csanyi (1957); G. Edwards (1953); Emeléus *et al.* (1934); Fireman and Schwarzer (1957); Friedman (1953; 1955; 1956); Friedman *et al.* (1956); Geiss, Oeschger, and Signer (1958); Heller (1957); Jensen (1953b); Kaufman and Libby (1954); Knop (1955); Korff (1954); Ludwick (1958); Oana (1939); Riesenfield and Chang (1936); Roth (1956); Roy and Roy (1957); Suess (1953); Teis and Florenskiĭ (1940); Varshavskiĭ and Vaisberg (1955); Weston (1955); Wirth, Thompson and Utterback (1935)

Indium (49)

Soils*—(no data) Igneous rocks*—(±0.1)

Iron and sulfide meteorites—compilation by H. Brown (1949, p. 626)

Silicate meteorites—calculated value in brackets by Shaw (1952b)

Igneous rocks, deep-sea sediments, shales (S8, S39, and S13 below detectable limit and assumed zero—other shales taken are S1, S2, S15, S16, and S17), coal, schists, and rock salt (below detectable limit—noted on Table as < 0.02 ppm), graywacke (not on Table 2—S38, S37, S36—$0.10_{0\text{-}12^3}$ ppm)—Shaw (1952b)

Sandstone—compilation by Krauskopf (1955a, p. 416)

Coal ash—maximum of 5 ? ppm in compilation by Krauskopf (1955a, p. 418)*

Minerals—Anderson (1953)*

General*—Shaw (1957a); Wager, Smit, and Irving (1958)

Isotopes*—Sampson and Bleakney (1936)

Iodine (53)

Soils*—5 Igneous rocks*—0.4

Iron and silicate meteorite (Mocs)—compilation by Correns (1956, p. 183), values rounded for iron meteorites

Pegmatite—compilation by Correns (1956, p. 190)

Shales—superscript of 11, Itkina (1956)

Sandstone and limestone—Itkina (1956)

Sea water—Sugawara and Tereda (1957)*

Marine evaporates—Lang (1954)*

General*—Savchenko (1956); Chilean Iodine Educational Bureau (1956)

Iridium (77)

Soils*—(no data) Igneous rocks*—(~0.001)

Silicate and iron meteorites—compilation by H. Brown (1949), p. 626)

Isotope abundance*—J. R. Sites (in preparation)

Iron (26)

Soils*—38000 Igneous rocks*—46500

Iron meteorites—H. Brown (1949, p. 626); Henderson and Perry (1954)

Silicate phase of chondrites—superscript of 96, computed from Urey and Craig (1953) and Wiik (1956) by this author

Limestones—Lamar (1957)*

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota). This value is somewhat high because of iron-filing contamination in samples 7, 11, 13, and 14.

Rock salt—Thompson and Wardle (1954, p. 177)

General*—Correns (1952); Abramovich (1957a)

Isotopes*—Valley and Anderson (1941)

Krypton (19)

Soils*—(no data) Igneous rocks*—

Meteorites—Gerling and Baranovskaya (1956)*

Igneous rocks—estimated at 4.2×10^{-9} cc/gm Turekian (in press)*

Atmosphere*—Damon and Kulp (1958)

Isotopes*—Tomlinson, Fleming, and Thode (1954)

Lanthanum (57)

Soils*—(no data) Igneous rocks*—40

Atomic radius—Pácal (1957a; 1957b)*

Igneous rocks—including abundance values for other rare-earth elements, Tröger (1934)*

Shales—Minami (1935)*; Tongeren (1938)*

Sandstones and limestones—Rankama and Sahama (1950, p. 530). Values enclosed in parentheses with question mark by compiler.

Minerals—monazite, Murata, Rose, and Carron (1953)*; abundance ratios of rare-earth elements, Barinskiĭ (1958)*

Isotopes*—Korff (1954); Glover and Watt (1957)

Lead (82)

Soils*—10 Igneous rocks*—16

Sulfide phase of iron meteorites—Wedepohl (1956, p. 80), analyses 8–13

Iron phase of meteorites—C. Patterson (1953, p. 36); C. Patterson *et al.* (1953)*

Silicate phase of meteorites—C. Patterson (1955);* Marshall and Hess (1958)* (See note following section on Abundances.)

Igneous rocks—diabase, Fairbairn, Ahrens, and Gorfinkle (1953)*; granite, Deleon and Ahrens (1957)*; R. Kuroda and Gorai (1956). Data from Table 12 of Wedepohl (1956, p. 110) is graphed.

Deep-sea sediments—superscript of 15, Goldberg and Arrhenius (1958); superscript of 8; calcareous blue and red muds, Wedepohl (1956, p. 124, analyses 411–418); Globigerina ooze, Wedepohl (1956, p. 129–130, analyses 446–450)*: 163_{149^5} ppm Pb; Tatsumoto (1956–1957, Part XXIII)

Shales—superscript of 17, Ostrom (1957)

Sandstones—Wedepohl (1956, p. 127, analyses 425, 426, 428, 430, taken at 1 ppm, 431, taken at 1 ppm)

Limestones—superscript of 91, Ostrom (1957); others from Wedepohl (1956, p. 128–129, analyses 433, 436, 437, 438, 441, 442, 444, 445)

Continental sediments—Abramovich (1957b)*

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)

Metamorphic rocks—schist, superscript of 6; Wedepohl (1956, p. 136, analyses 492–495, 499–501); gneiss, superscript of 5, Wedepohl (1956, p. 136, analyses 502–506)

Asphalt and petroleum ash—average of 50–2000 ppm in compilation by Krauskopf (1955a, p. 419)

Isotopes* (some references of radiogenic isotope

included)—Broda and Jenkner (1951); Collins, Russell, and Farquhar (1953); Eberhardt, Geiss, and Houtermans (1955); Marshall (1957); Masuda (1958); Nier (1939b); C. Patterson *et al.* (1953); C. Patterson (1955); Paul (1956); Russell, Collins, and Farquhar (1952); Russell (1956); Sakai and Satō (1958); Starik and Sobotovich (1956); Starik *et al.* (1957); Tilton *et al.* (1955); Zhirov, Zykov, and Stupnikova (1957).

General*—Yost (1957)

Lithium (3)

Soils*—30 Igneous rocks*—50

Chondrites—Pinson, Ahrens, and Franck (1953, p. 253)

Ultramafic rocks—Pinson, Ahrens, and Franck (1953, p. 253)*

Granite—Deleon and Ahrens (1957)*

Igneous rocks, shales (superscript of 26), sandstones, laterites, hornfels, gneiss (6 weathered), near-shore sediments (56_6^{10} ppm—not on Table 2)—Horstman (1957)

Limestone—Goldschmidt (1954, p. 136)

Marble—Lelong and Hodge (1954)

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)

Isotopes*—Brewer and Baudisch (1937); Cameron (1953); Fireman and Schwarzer (1957); Gillieson and Thorne (1955); Sampson and Bleakney (1936); T. I. Taylor and Urey (1938)

General*—Ginzburg (1958)

Lutetium (71)

Soils*—(no data) Igneous rocks*—(1)

Isotopes*—Dixon, McNair, and Curran (1954); Herr and Merz (1957); Herr *et al.* (1958)

Magnesium (12)

Soils*—6000 Igneous rocks*—17000

Iron phases of meteorites—compilation by H. Brown (1949, p. 626)

Limestone—Lamar (1957)*

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)

Minerals—serpentine, Nagy and Faust (1956)

Hydrocarbons—Baker and Hodgson (1959)*

Isotopes*—Rankama (1954g)

Manganese (25)

Soils*—850 Igneous rocks*—1000

Sulfide and iron phases of meteorites—compilation by H. Brown (1949, p. 626)

Igneous rocks—norite, Stonehouse (1954)*

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)

General*—Ilchenko (1957); Abramovich (1957a)

Mercury (80)

Soils*—(~0.01) Igneous rocks*—0.06

Sulfide meteorites—compilation by H. Brown (1949, p. 626)

Marl and carbonate—Heide and Böhm (1957). Hg is enriched in marl relative to pure carbonate. A similar trend may be observed for other trace elements in Paleozoic shales of Illinois relative to associated carbonates (Ostrom, 1957).

Sandstone—compilation by Krauskopf (1955a, p. 416)

Generals*—Stock and Cucuel (1934); Contini (1953); Saukov (1946)

Isotopes*—Grigor'ev *et al.* (1958)

Molybdenum (42)

Soils*—3 Igneous rocks*—1.7

Meteorite phases—Kuroda and Sandell (1954)

Igneous rocks—solid circles on Table 2, Kuroda and Sandell (1954); dashes, Vinogradov, Vaĭnsteĭn, and Pavlenko (1958); intrusive rocks, Studenikova, Glinkina, and Pavlenko (1957)*, Rabinovich, Murav'eva, and Zhdanova (1958)*; extrusive rocks, Ishimori (1951)*

Sedimentary rocks—deep-sea sediments (superscript of 6—other entry is from Goldberg and Arrhenius, 1958); shales (superscript of 26, exclusive of shales with organic matter or sulfide, *i.e.*: 2 vanadiniferous shales, Paris-Bloomington district, Idaho, 1 calcareous shale, Windy Creek area, Alaska, 1 organic shale, Katella area, Alaska, epidote-phase shale, Black Hills, South Dakota, 1 pyrite-phase shale, Interstate Park, Wisconsin); the other shale entry is from Ostrom (1957); sandstones and arkose, carbonates (superscript of 12—the other entry is from Ostrom, 1957); slates—Kuroda and Sandell (1954)

Shales—The composited sample analyzed, prepared by Dr. A. B. Ronov, represents 7614 clays of different ages and facies of the Russian Platform (Vinogradov, Vaĭnsteĭn, and Pavlenko, 1958, p. 407)

Sandstones—The composited sample analyzed, prepared by Dr. A. B. Ronov, represents 6107 sandstones of different ages and facies of the Russian Platform (Vinogradov, Vaĭnsteĭn, and Pavlenko, 1958, p. 407)

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)

Asphalt and petroleum ash—average of 50–1500 ppm in compilation by Krauskopf (1955a, p. 419)*

Coal—Korolev (1957)*, 9 ppm in Bylymskiĭ coal deposit

Minerals—umohoite, Kerr *et al.* (1957, p. 66)

Isotopes*—Broda and Jenkner (1951)

General*—Gamaleev and Khamrabaev (1958)

Neodymium (60)

Soils*—(no data) Igneous rocks*—30

Isotopes*—Broda and Jenkner (1951); Porschen

and Riezler (1953); Tomlinson, Petruska, and Malaika (1955)

Neon (10)

Soils*—(no data) Igneous rocks*—?

Iron meteorites—Gerling (1956)*

Stony meteorite—Nuevo Laredo achondrite, Reynolds and Lipson (1957)

Igneous rocks—estimated 7.7×10^{-8} cc/gm, Turekian (in press)*

Atmosphere*—Damon and Kulp (1958)

Isotopes*—Wetherill (1954)

Neptunium (93)

Soils*—(no data) Igneous rocks*—?

Pitchblende—Seaborg and Perlman (1948)

Nickel (28)

Soils*—40 Igneous rocks*—100

Sulfide meteorites—compilation by H. Brown (1949, p. 626)

Iron meteorites—superscript of 91, Goldberg, Uchiyama, and Brown (1951)*; Nichiporuk (1958)*; Henderson and Perry (1954)*

Stony iron meteorites—superscript of 9, Lovering *et al.* (1957, p. 272)

Granites—Kuroda and Gorai (1956)

Volcanic rocks—Katsura (1956, Parts XXXVI, XXXVII)

Basalt—Turekian (1956), numerical value indicated

Diabase—Fairbairn, Ahrens, and Gorfinkle (1953); Storm and Holland (1957)*; norite—Stonehouse (1954)*

Schist—Shaw (1956)

Deep-sea deposits—Hutchinson *et al.* (1955)*; Pettersson and Rotschi (1952)*; Tatsumoto (1956–1957, Parts XXI, XXII)*

Sandstone—compilation by Krauskopf (1955a, p. 416)

Crude oil—Hyden (1955); Nagashima and Machin (1957)*

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)*, not detected to 100 ppm

Asphalt and petroleum ash—compilation by Krauskopf (1955a, p. 419*, average of 1000–45000 ppm

Rock salt—Thompson and Wardle (1954, p. 177)

General*—Wells (1946); Lombard (1956)

Niobium (41)

Soils*—(no data) Igneous rocks*—20

Iron meteorites—compilation by H. Brown (1949, p. 626)

Igneous rocks and general*—Znamensky (1957)

Sea water—Carlisle and Hummerstone (1958)

General*—Pavlenko, Vaĭnshteĭn, and Kakhana (1958)

Nitrogen (7)

Soils*—1000 Igneous rocks*—?

Deep-sea sediments—superscript of 28, Edgington and Byers (1942, p. 153), exclusive of three analyses of cores from offshore Ocean City, Maryland; superscript of 7, Zaitseva (1956), N in ammonia only

Recent marine (nonpelagic)—superscript of 34, Bader (1955)

Limestone—Ilchenco and Mendes (1957)

Coal—Lidin and Ettinger (1949)*

Hydrocarbons—Hyden (1955); Nagashima and Machin (1957)*

Natural gas*—C. C. Anderson and Hinson (1951); Anonymous (1954)

Isotopes*—Dole *et al.* (1954); Dole (1956); Eriksson (1958); Korff (1954); Hoering (1955; 1956; 1957; 1958); Hoering and Moore (1958); Junk and Svec (1958); Mayne (1957b); McQueen (1950); Nier (1950); Parwel, Ryhage, and Wickman (1957); White and Yagoda (1950)

Osmium (76)

Soils*—(no data) Igneous rocks*—(~0.0001?)

Iron meteorites—compilation by H. Brown (1949, p. 626)

Silicate meteorites—Rankama and Sahama (1950, p. 689)

Isotopes*, radiogenic—Hinterberger, Herr, and Voshage (1954); Geiss *et al.*, (1958)

Oxygen (16)

Soils*—490000 Igneous rocks*—473000

Iron and sulfide phase of meteorites—compilation by H. Brown (1949, p. 626)

Chondrites—superscript of 96, recalculated and screened from Urey and Craig (1953) and Wiik (1956) by this author

Deep-sea sediments, sandstones, carbonates—calculated from water-free averages (Green and Poldervaart, 1958)

Isotopes*—Baertschi (1950; 1951; 1957); Baertschi and Silverman (1951); Baertschi and Schwander (1952); Brodskiĭ and Lunenok-Burmakina (1955); J. B. Brown (1957); Brownlow (1957); Clayton and Epstein (1958), Dansgaard (1953a; 1954a; 1954b); Dole (1956); Dole *et al.* (1954); Dontsova (1952; 1954; 1955a; 1955b; 1956); Epstein (1956); Epstein *et al.* (1953); Epstein and Mayeda (1953); Epstein and Sharp (1959); Kerwin, McElcherin, and Cottin (1957); Emiliani (1954; 1955a; 1955b; 1956a; 1956b; 1957); Hoekstra (1956); Holmes (1956); D. A. Hutchinson (1954); Karpacheva and Rozen (1953); Keith *et al.* (1953); Korff (1954); Lane (1955); Leighton (1954); Lowenstam and Epstein (1954); Miyake (1952); Nier (1950); Perederev (1955; 1957); Roake and Dole (1950); Schwander (1953); S. R. Silverman (1951); Tanatar (1952); Taube (1956); Teis (1950; 1951; 1954; 1955;

1956); Teis and Florenskiĭ (1940); Teis, Chupakhin, and Naydin (1957); Tokuda (1956); Tokuda and Ao (1956); Wiseman (1954)

Palladium (46)

Soils*—(no data) Igneous rocks*—(0.02)
Sulfide and silicate meteorites—compilation by H. Brown (1949, p. 626)
Iron meteorites—superscript of 45, Goldberg, Uchiyama, and Brown (1951, p. 16–17)
Igneous rocks—Vincent and Smales (1956)*
Coal ash—Goldschmidt (1954, p. 694)
Isotopes*—Ordzhanikidze and Zubareva (1957); Sites, Consolazio, and Baldock (1953)

Phosphorus (15)

Soils*—800 Igneous rocks*—900
Iron and sulfide meteorite phases—compilation by H. Brown (1949, p. 626)
Silicate phase of chondrites—superscript of 66, recalculated and screened from Urey and Craig (1953) and Wiik (1956) by this author
Deep-sea sediments—Edgington and Byers (1942, p. 153), exclusive of three analyses of cores from offshore Ocean City, Maryland
Sandstones and carbonates—Clarke (1924)
Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)
General*—Gulik (1955); Savul and Botez (1955); Fesenkova (1955). Fesenkova's analytical data indicate that, of the two organic phosphorus compounds (phytins and nucleonic acid types), only the phytin-type compounds survive diagenesis

Platinum (78)

Soils*—(no data) Igneous rocks*—(0.005)
Iron and meteorite phases—compilation by H. Brown (1949, p. 626)
Isotopes*—Porschen and Riezler (1953)

Plutonium (94)

Soils*—(no data) Igneous rocks*—?
Pitchblende—Seaborg and Perlman (1948)

Polonium (84)

Soils*—(no data) Igneous rocks*—2×10^{-10}
Iron meteorites—Rankama and Sahama (1950, p. 782)
Volcanic ash—Yamamoto (1957)

Potassium (19)

Soils*—13600 Igneous rocks*—25000
Chondrites—G. Edwards (1955); G. Edwards and Urey (1955)*; Hurley (1957)*; Ahrens, Pinson, and Kearns (1952, p. 236)*; Pinson, Ahrens, and Franck (1953)*, not included on Table 2: 900_{230}[21] ppm
Igneous rocks—dunite, Holyk and Ahrens (1953); Ahrens, Pinson, and Kearns (1952)
Marble—Lelong and Hodge (1954)
Limestone—Lamar (1957)*
Sandstone—Murray and Adams (1958)
Bauxites—J. A. S. Adams (Personal communication)
Evaporites—Lang (1954)*
Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)
Sediments, general*—Canney (1952)
General*—Demin and Khitarov (1958); Larios (1950)
Isotopes*—Some references on radiogenic K included—A. K. Brewer (1938); 1939a); Brewer and Baudisch (1937); McNair, Glover, and Wilson (1956). Half life of K^{40}—Nier (1950); Reuterswand (1952); Rik (1954); Schumb, Evans, and Leader (1941); Smythe (1939); Taylor and Urey (1938); Wetherill (1953)

Praseodymium (59)

Soils*—(no data) Igneous rocks*—7
Isotopes*—Broda and Jenkner (1951)

Promethium (61)

General*—Lavrukhina (1958)

Protactinium (91)

Soils*—(no data) Igneous rocks*—9×10^{-7}
Isotopes*—Schumb, Evans, and Hastings (1939)

Radium (88)

Soils*—8×10^{-7} Igneous rocks*—9×10^{-7}
Meteorite phases—Davis (1950, p. 110)
Igneous rocks—ultramafic rocks, G. L. Davis (1947; 1950); volcanic rocks, Asayama (1953)*; extrusive rocks, Shavrova (1958)*
Deep-sea sediments—H. D. Holland (1952, unpub. PhD thesis, Columbia Univ.)*; Holland and Kulp (1954)*; Hecht (1953)*; Kroll (1957)*; Rona and Urry (1952)*; Pettersson (1953, p. 250), 1.3 to 52 ppm in red clay quoted as 1–50; Bernert (1951)*; G. Arrhenius and Bramlette (1957)*
Continental sediments—Umemoto and Sakanoue (1958)*
General*—P. K. Kuroda (1955, paper presented at the Symposium on geochemistry, Div. Physical and Inorganic Chemistry, Am. Chemical Society, September 12, 1955

Radon (86)

Soils*—(no data) Igneous rocks*—6×10^{-12}
Natural gas—Faul *et al.* (1954)

Atmosphere*—Small, Lillegraven, and Storebø (1958)

Rhenium (75)

Soils*—(no data) Igneous rocks*—(~0.001)

Meteorite phases—Rankama and Sahama (1950, p. 654)

Iron meteorites—Goldberg and Brown (1949)

Minerals—Herr and Merz (1955)*; Peterson, Hamilton, and Myers (1957)*; in molybdenite, Studenikova and Zolotareva (1958)*

General*—Noddack and Noddack (1931)

Isotopes—Suttle and Libby (1954)*; Herr, Hinterberger, and Voshage (1954)*; Herr and Merz (1958), half life of Re^{187} cited in Table 2 as 6.2×10^{10} years from reported values of $5.5–6.8 \times 10^{10}$ years; Naldrett (1958)*

Rhodium (45)

Soils*—(no data) Igneous rocks*—(0.001?)

Silicate and iron meteorites—compilation by H. Brown (1949, p. 626)

Coal ash—Goldschmidt (1954, p. 694)

Rubidium (37)

Soils*—60 Igneous rocks*—280

Chondrites—Pinson, Ahrens, and Franck (1953), superscript of 21; Cabell and Smales (1957, p. 404)*; Ahrens, Pinson, and Kearns (1952, p. 236)*; Webster, Morgan, and Smales (1958, p. 151)

Igneous rocks—Ahrens, Pinson, and Kearns (1952); Horstman (1957); granite, Deleon and Ahrens (1957)*; Tauson and Stavrov (1957)*; Sazhima (1958)*

Deep-sea sediments—red clay, including 2 composites—Horstman (1957)

Hornfels—Horstman (1957)

Marble—Lelong and Hodge (1954)

Shales—superscript of 323, Canney (1952); superscript of 26, Horstman (1957)

Sandstones, laterites, and carbonates—Horstman (1957); analyses of near-shore sediments by Horstman not included on Table 2: $128_6{}^{10}$ ppm

Sea water—Smales and Webster (1957)

Minerals—lepidolite and beryl, Cabell and Smales (1957, p. 401–402)

Isotopes—half life, Davis *et al.* (1957); Huster (1956)* gives a half life of $4.0–4.5 \times 10^{10}$ years; A. K. Brewer (1938)*; Pinson *et al.* (1957)*; Hurley (1958)*

General*—Demin and Khitarov (1958)

Ruthenium (44)

Soils*—(no data) Igneous rocks*—(±0.0001?)

Silicate and iron meteorites—compilation by H. Brown (1949, p. 626)

Minerals—Noddack and Noddack (1931)*

General*—Zviagintsev (1950)

Isotopes*—Broda and Jenkner (1951); Sites (1956, p. 152)

Samarium (62)

Soils*—(no data) Igneous rocks*—(4)

Isotopes—half life of Sm^{147}, Beard and Wiedenbeck (1954); Tomlinson, Petruska, and Malaika (1955)*

Scandium (21)

Soils*—(no data) Igneous rocks*—13

Universe—Ahrens (1956)*

Chondrites—Pinson, Ahrens, and Franck (1953, p. 253)

Igneous rocks—diabase, Fairbairn, Ahrens, and Gorfinkle (1953); Lyakhovich (1957)*; dunite, Pinson, Ahrens, and Franck (1953)

Red clay—Young (1954)

Sandstones, limestones, and coal ash—compilation by Krauskopf (1955a, p. 416, 416, and 418, respectively)

Asphalt and petroleum ash—compilation by Krauskopf (1955a, p. 419)

General*—Burkser *et al.*, (1955), a monograph with quantitative and semiquantitative data for about 600 samples. *See also* Borisenko (1957) and Kalenov (1958)

Selenium (34)

Soils*—0.01 Igneous rocks*—(0.01)

Iron, sulfide, and silicate meteorites—compilation by H. Brown (1949, p. 626)

Igneous rocks—Sindeeva (1957)*; 0.14 ppm Se, regional average, Sindeeva and Kurbanova (1958)*

Sedimentary rocks—0.0001–0.1 ppm Se, regional range, Sindeeva and Kurbanova (1958)*; sandstones and carbonates, compilation by Krauskopf (1955a, p. 416)

Metamorphic rocks—schists 0.3 to abnormal 9 ppm Se, Sindeeva and Kurbanova (1958)*

Deep-sea sediments—Edgington and Byers (1942, p. 153), exclusive of three analyses of cores from offshore Ocean City, Maryland; the "less than" symbol for nine samples was ignored in computing the average and standard deviation. Therefore, these numbers are too high by an unknown but probably small amount.

General*—Borchert (1955); Trelease and Beath (1949); Sargent (1955)

Silicon (14)

Soils*—330000 Igneous rocks*—291000

Iron meteorites—compilation by H. Brown (1949, p. 626)

Chondrites—Suess and Urey (1956); silicate phase of chondrites, superscript of 96, recalculated and screened from Urey and Craig (1953) and Wi (1956) by this author

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)

General*—Cipriani (1954); Kubach (1952a; 1952b)

Isotopes*—Allenby (1954); Grant (1954); Korff (1954); Reynolds (1953a; 1953b); Reynolds and Verhoogen (1953)

Silver (47)

Soils*—(no data) Igneous rocks*—(0.2)

Sulfide meteorites—Hess, Marshall, and Urey (1957)

Iron meteorites—compilation by H. Brown (1949, p. 626)

Chondrites—Onishi and Sandell (1957, p. 269), calculated; Hess, Marshall, and Urey (1957)

Diabase—Fairbairn, Ahrens, and Gorfinkle (1953)

Sandstones and carbonates—compilation by Krauskopf (1955a, p. 416)

Hydrocarbons—compilation by Krauskopf (1955a, p. 419)

General*—Borchert (1955)

Sodium (11)

Soils*—6300 Igneous rocks*—25000

Meteorites—G. Edwards (1955); Edwards and Urey (1955)

Limestone—Lamar (1957)*

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)

Marble—Lelong and Hodge (1954)

Isotopes*—Korff (1954); Sampson and Bleakney (1936); Marquez, Costa, and Almeida (1957)

Strontium (38)

Soils*—300 Igneous rocks*—350

Chondrites and ultramafic rocks—Pinson, Ahrens, and Franck (1953, p. 253)

Igneous rocks—Turekian and Kulp (1956); Gerasimovskiĭ and Lebedev (1958)*; diabase, Fairbairn, Ahrens, and Gorfinkle (1953)*; granite, Cocco (1953)*

Shales—superscript of 69, Turekian and Kulp (1956); superscript of 17, Ostrom (1957)

Sandstones—compilation by Krauskopf (1955a, p. 416)

Carbonates—superscript of 91, Ostrom (1957); Kulp, Turekian, and Boyd (1952)*

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)

Asphalt and petroleum ash—average of 500–1000 ppm in compilation by Krauskopf (1955a, p. 419)*

General*—Heide and Christ (1953)

Isotopes* (including radiogenic isotopes)—Ahrens (1948); Aldrich, Herzog, Holyk, Whiting, and Ahrens (1953); Aldrich, Herzog, Doak, and Davis (1953); Broda and Jenkner (1951); Ewald, Garbe, and Ney (1956); Gast (1955); Herzog, Pinson, and Hurley (1954); Herzog *et al.* (1955); Hurley (1958); Pinson *et al.* (1957); Sampson and Bleakney (1936)

Sulfur (16)

Soils*—850 Igneous rocks*—900

Sulfide and iron meteorites—compilation by H. Brown (1949, p. 626)

Chondrites—the relatively high value shown on Table 2 is due to inclusion of sulfides according to Vinogradov (1956, p. 44)

Deep-sea sediments—Edgington and Byers (1942, p. 153), exclusive of three analyses of cores from offshore Ocean City, Maryland

Hydrocarbons—Hyden (1955)

Isotopes*—Ault (1955); Bateman and Jensen (1956); Bonython and King (1956); Eberhardt, Geiss, and Houtermans (1955); Jensen (1957); G. E. Jones (1956, unpub. PhD thesis, Rutgers Univ.); Jones and Starkey (1957); Jones *et al.* (1956); Kulp, Ault, and Feely (1956a; 1956b); Kulp *et al.* (1956); Lazard, Nief, and Roth (1952); McKinstry (1957); Macnamara (1951); Macnamara *et al.* (1952); Macnamara and Thode (1950; 1951); Rafter, Wilson, and Shilton (1958); Rankama (1952); Sakai (1957); Sakai and Nagasawa (1958); Thode (1954; 1955); Thode, Macnamara, and Fleming (1953); Thode, Wanless, and Wallouch (1953; 1954); Trofimov (1949a); Vinogradov, Chupakhin, and Grinenko (1956; 1957); Vinogradov *et al.* (1956)

Tantalum (73)

Soils*—(no data) Igneous rocks*—2.7

Iron meteorites—compilation by H. Brown (1949, p. 626)

Igneous rocks—Znamensky (1957)

General*—Pácal (1957b); Ginzburg (1956); Pavlenko, Vainstein, and Kakhana (1958)

Isotopes*—White, Collins, and Rourke (1955)

Technetium (43)

Soils*—(no data) Igneous rocks*—?

Occurrence in nature—Herr (1954)*; Boyd and Larson (1956)

Tellurium (52)

Soils*—(no data) Igneous rocks*—($\pm$0.001)

Sulfide and silicate meteorites—compilation by H. Brown (1949, p. 626)

Chondrites—compilation by Urey (1952, p. 252), 0.13 ppm; calculated value of $\sim$1 ppm from Onishi and Sandell (1957, p. 269)

Isotopes*—Hayden and Inghram (1953); Inghram and Reynolds (1954)

Terbium (65)

Soils*—(no data) Igneous rocks*—($\sim$1)

Thallium (81)

Soils*—(no data) Igneous rocks*—1.7

Meteorites—sulfide phase, compilation by H. Brown (1949, p. 626)*; silicate phase of chondrites, Shaw (1952a)* (See note following section on Abundances)

Igneous rocks—Shaw (1952a); higher values are reported for composites of Japanese volcanic rocks by Ishimori and Takashima (1955, p. 72)*; basalt —0.3 ppm T1, andesite 1.0 ppm T1, dacite 1.1 ppm T1, rhyolite 1.2 ppm T1. *See also* Tauson and Buzayev (1957)* and Zlobin (1958)*.

Sedimentary rocks—deep-sea sediments, sandstones, graywackes, arkoses, limestones, dolomites, halites, and shales (superscript of 8)—Shaw (1952a); shales (superscript of 323), Canney (1952). Higher values of T1 are reported in analyses of composites of shales by Ishimori and Takashima (1955, p. 73)*: 14 Japanese Paleozoic shales, 2.2 ppm T1, 10 Japanese Mesozoic shales, 2.4 ppm T1, 36 European Paleozoic shales, 2.2 ppm T1

Metamorphic rocks—gneisses and slates, Shaw (1952a)

Asphalt-petroleum ash and coal ash—compilation by Krauskopf (1955a, p. 419* and 418 respectively)

General*—Shaw (1957a); Murakami (1950); Ivanov (1958); Voskresenkaya and Karpova (1958); Demin and Khitarov (1958)

Isotopes*—Golubchina, Rabinovich, and Murtazina (1957)

Thorium (90)

Soils*—6 Igneous rocks*—13

Sulfide meteorites—compilation by H. Brown (1949, p. 626)

Iron meteorites—Dalton *et al.* (1953, p. 283); Dalton and Thompson (1954, p. 80)*. In the 1953 reference, the values selected were from the scintillation-counting combined U-Th technique for Bethany (Amalia Krantz), Bethany (Harvard), Carbo, Muonionalusta II (taken at 0.011 ppm), San Martin, Tocopilla (taken at 0.0100 ppm) and Toluca Durham (taken at 0.0060 ppm). The 1954 data for Bethany (Harvard) indicate that the 1953 value may be too high by a factor of 2. The range of Th in iron meteorites given by Bate, Potratz, and Huizenga (1958)* is 6×10^{-6} to 20×10^{-6} ppm.

Silicate meteorites—Hurley (1957)*

Chondrites—Bate, Huizenga, and Potratz (1957)

Granite—Tilton *et al.* (1955)*; Komlev *et al.* (1956)*; Husmann (1956)*; Larsen *et al.* (1955)*

Igneous rocks—extrusive rocks, Shavrova (1958)*

Deep-sea sediments—Picciotto and Wilgain (1954)*; Baranov and Kuzmina (1957)*; Koczy (1949)*; H. D. Holland (1952, unpub. PhD thesis, Columbia Univ.)*; Holland and Kulp (1954)*; E. D. Goldberg (Personal communication)

Shales—J. A. S. Adams (Personal communication); Baranov, Ronov, and Kunashova (1956)*

Sandstones—Murray and Adams (1958)

Carbonates—superscript of 51, J. A. S. Adams (Personal communication); Baranov, Ronov, and Kunashova (1956)*

Rock salt—Thompson and Wardle (1954, p. 178

Sediments, general*—Adams, Richardson, and Templeton (1958)

Sea water—Koczy *et al.* (1957)*

Minerals—Frondel (1955)

General*—Cooper (1953–1958)

Isotopes*—Tilton *et al.* (1955); Starik *et al.* (1958); Th^{232} (half life), Senftle (1956)

Thulium (69)

Soils*—(no data) Igneous rocks*—(1)

General*—Kogan (1957)

Tin (50)

Soils*—~10 Igneous rocks*—32

Iron meteorites—superscript of 19, Onishi and Sandell (1957); superscript of 8, Winchester and Aten (1957)

Iron phase of chondrites—Onishi and Sandell (1957)

Chondrites—Onishi and Sandell (1957)

Granite—Barsukov and Pavlenko (1956)

Deep-sea sediments—Tatsumotu (1956–1957, Part XXIII)

Limestones, asphalt and petroleum ash—compilation by Krauskopf (1955a, p. 416, 419)

Minerals—native tin, Turovskiĭ (1956)

General*—Barsukov (1957)

Titanium (22)

Soils*—4600 Igneous rocks*—4400

Iron meteorites—compilation by H. Brown (1949, p. 626)

Silicate phase of chondrites—superscript of 60, recalculated, screened, and recomputed from Urey and Craig (1953) and Wiik (1956) by this author

Igneous rocks—norite, Stonehouse (1954)*; granite, Znamensky (1958)*

Deep-sea sediments—Correns (1954)*

Shales—superscript of 17, Ostrom (1957)

Limestones—Lamar (1957)*

Bauxites—Bárdossy and Bárdossy (1954), based on 7 composites of a total of 7668 analyses

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)

Isotopes*—Broda and Jenkner (1951); Hess and Inghram (1949)

Tungsten (74)

Soils*—(no data) Igneous rocks*—? (2)

Sulfide phase of meteorites—compilation by Rankama and Sahama (1950, p. 625)

Silicate and iron meteorites—compilation by H. Brown (1949, p. 626)

[3] Vinogradov, Valnsteĭn, and Pavlenko (1958) crustal average.

Igneous rocks—Vinogradov, Vaĭnsteĭn, and Pavlenko (1958); Znamensky (1957)*; volcanic rocks, Kuroda (1956–1957, Part V)*; Sandell (1946)*; Ginzburg (1956)*

Shales—The composited sample analyzed, prepared by Dr. A. B. Ronov, represents 7614 clays of different ages and facies of the Russian Platform (Vinogradov, Vaĭnsteĭn, and Pavlenko, 1958, p. 407)

Sandstones—The composited sample analyzed, prepared by Dr. A. B. Ronov, represents 6107 sandstones of different ages and facies of the Russian Platform (Vinogradov, Vaĭnsteĭn, and Pavlenko, 1958, p. 407).

General*—Pácal (1957b)

Isotopes*—Porschen and Riezler (1953)

Uranium (92)

Soils*—1 Igneous rocks*—2.6

Iron meteorites—Patterson *et al.* (1953)*; Reed and Turkevich (1955)*; Dalton *et al.* (1953)*; Dalton and Thompson (1954)*; Starik and Shats (1956)*; Reed, Hamaguchi, and Turkevich (1958)

Chondrites—Urey (1956)*; Hurley (1957)*; superscript of 4, Hamaguchi, Reed, and Turkevich (1957); Hernegger and Wänte (1957)*

Igneous rocks—Komlev *et al.* (1956)*; Husmann (1956)*; granite, Tilton *et al.* (1955)*; pegmatite, Page (1950)*; Larsen *et al.* (1955)*; granites, Coulomb, Goldsztein, and LeMercier (1958)*

Deep-sea sediments—Baranov and Kuzmina (1957); G. Arrhenius and Bramlette (1957)*; Hecht (1953)*

Continental sediments—Umemoto and Sakanoue (1958)*

Shale and bauxite—J. A. S. Adams (Personal communication); Baranov, Ronov, and Kunashova (1956)

Sandstone—Murray and Adams (1958)

Carbonates—Baranov, Ronov, and Kunashova (1956)

Rock salt—not on Table 2, 1.7[1] ppm, Thompson and Wardle (1954, p. 178)*

Evaporites—K. G. Bell (1955)*

Coal—Breger and Schopf (1955, p. 290)*; not on Table 2, 188$_{77}$[4] ppm, Chattanooga formation

Hydrocarbons—Hyden (1955)

Sea water—Koczy, Tomic, and Hecht (1957)*; H. D. Holland (1952, unpub. PhD thesis, Columbia Univ.)*; Holland and Kulp (1954)*; Rona and Urry (1952)*

Minerals—uranophane, Gorman and Nuffield (1955, p. 638)

General*—Fischer (1955); Adams, Richardson, and Templeton (1958); Cooper (1953–1958); Yost (1957)

Isotopes*—Nier (1939a); Tilton *et al.* (1955)

Vanadium (23)

Soils*—100 Igneous rocks*—90

Sulfide phase of meteorites—Goldschmidt (1954, p. 486)

Iron meteorites—compilation by H. Brown (1949, p. 626)

Igneous rocks—volcanic rocks, Katsura (1956, Parts XXXIII–XXXV); R. P. Fischer (1955)*; diabase, Fairbairn, Ahrens, and Gorfinkle (1953)*; norite, Stonehouse (1954)*

Recent marine sediments—Romm (1956a)*

Sandstone and carbonate—compilation by Krauskopf (1955a, p. 416)

Hydrocarbons—Hyden (1955); Nagashima and Machin (1957)*

Asphalt and petroleum ash—average of 500–25000 ppm in compilation by Krauskopf (1955a, p. 419)*

General*—Badalow (1956); Gamaleev and Khamrabaev (1958)

Isotopes*—Hess and Inghram (1949); Leland (1949)

Xenon (54)

Soils*—(no data) Igneous rocks*—?

Stony meteorites—Nuevo Laredo achondrite, Reynolds and Lipson (1957); Gerling and Baranovskaya (1956)*

Igneous rocks—estimated 3.4×10^{-10} cc/gm, Turekian (in press)*

Atmosphere*—Damon and Kulp (1958)

Isotopes*—Tomlinson, Fleming, and Thode (1954)

Ytterbium (70)

Soils*—(no data) Igneous rocks*—(2)

Yttrium (39)

Soils*—(no data) Igneous rocks*—20

Sandstone and carbonate—compilation by Krauskopf (1955a, p. 416)

Coal ash—Rankama and Sahama (1950, p. 332)

Zinc (30)

Soils*—50 Igneous rocks*—80

Sulfide meteorites (5 troilite inclusions) and iron meteorites—Noddack and Noddack (1930)

Chondrites—Onishi and Sandell (1955b); compiler's value from stated approximate limits, *i.e.*, 90 and 150 ppm

Igneous rocks, solid circles in Table 2 (volcanic rocks—triangles)—Katsura (1956, Part XL)

Deep-sea sediments (analyses 161–170), shales (analyses 171–180), sandstones (analyses 192–196), graywackes (analyses 198–204), limestones (analyses 206–209), dolomites (analyses 210–212), and coal (analyses 235–236)—Wedepohl (1953)

Shale (superscript of 17) and carbonate (superscript of 91)—Ostrom (1957)

Deep-sea sediments—Tatsumoto (1956–1957)*

Asphalt and petroleum ash—average of 100–2500 ppm in compilation by Krauskopf (1955a, p. 419)*

General*—Morita (1954)

Isotopes*—Broda and Jenkner (1951); Blix, Ubisch, and Wickman (1957); Hess, Inghram, and Hayden (1948); Kerwin, McElcheran, and Cottin (1957)

Zirconium (40)

Soils*—300 Igneous rocks*—170

Iron meteorites—compilation by H. Brown (1949, p. 626)

Chondrites—superscript of 21 inclusive of one high value (Lumpkin), Pinson, Ahrens, and Franck (1953, p. 253); Pinson and Ahrens (1952)*

Ultramafic rocks—Pinson, Ahrens, and Franck (1953); Pinson and Ahrens (1952)*

Iron meteorites, deep-sea sediments (globigerina ooze, superscript of 3, analyses 272–274; red clay, superscript of 3, analyses 234–236), shales, superscript of 24 (analyses 209–232), sandstones (analyses 237–245, 247, 255), graywackes (analyses 251–254), schists and phyllites (analyses 280, 281, 285–287; if analysis 281 of 2500 ppm Zr is discarded, the average and standard deviation fall below 100 ppm Zr), quartzites (analyses 246–250), coal (analyses 194–196), halite (analyses 190–193; no. 192 taken at 0.1; reported as <0.1), evaporites, including gypsum (analyses 275–276), limestones (analyses 256–258, 261–271, superscript of 14), dolomite (analyses 259–260)—Degenhardt (1957)

Asphalt and petroleum ash—average of 50–500 ? ppm in compilation by Krauskopf (1955a, p. 419)*

Chert—J. A. Maxwell (1953, unpub. PhD thesis, Univ. Minnesota)*

Isotopes*—Broda and Jenkner (1951)

Sea water—Degenhardt (1957, footnote to p. 299), Atlantic surface water

General*—Abshire (1958), compilation citing 844 reports

Note: Abundances of Bi, Tl, Pb, and U in troilite from two iron meteorites, and Bi, Tl, and Pb in five chondrites (exclusive enstatite and carbonaceous types) included in Table 2. Data from G. W. Reed, K. Kigoshi, and A. Turkevich (1959, unpub. paper, *Tl, Pb, Bi, and U contents of meteorites*, presented at 40th annual meeting, Am. Geophys. Union, Washington, D. C., May 5, 1959).

Cost Range

The range in cost of each element was obtained from 23 American chemical supply companies.[4] Conversion was made to the specific weight or volume cited. The cost applies to reagent-quality material. Obviously the cost range could be expanded an order of magnitude in each direction to include elements of industrial or spectroscopic purity.

Series Data

Interpretation of Serial Changes in Open Systems

Many geologists find a serial change in minerals or rocks or the elements within them and attempt to reconstruct a probable history. Sometimes a model is used, such as a defective blast furnace or a broken test tube. Within a geologic time period in which even the natural "constants" may change (Wilkinson, 1958), gravity, heat, pressure, magnetic, and electrical potentials may have cumulative, discontinuous, nonexistent, or cancelling effects on earth materials. With an open system subject to these changing potentials over a time long enough to do almost anything thermodynamics says is possible, the geologist makes the "best" interpretation. Sometimes, with geochemical counsel and new and wonderful electronic tools and a sturdy hammer, this interpretation is unique. In any case, an awareness of the realities of nature may enable the geologist to discard the "imaginary number" for the "real" one, although both may be thermodynamically or mathematically correct.

The series data indicate elemental gradients of chemical, electrical, and thermodynamic parameters. Such serial changes measured or observed under ideal laboratory conditions may be compared with series obtained in nature.

Standard-Electrode Potentials, Electrochemical Equivalents, Entropies of Ions in Aqueous Solution, and Oxidation-Reduction Potentials

The numbers, their reliability, and detailed source data for these series are documented in Conway (1952, p. 290–239, 330–334, 304, and 25 respectively). Two pertinent geological papers include Garrels' (1954) work on the role of oxidation potentials in mineral genesis

[4] Baker and Adamson Products; J. T. Baker Chemical Company; The Beryllium Corporation; Brush Beryllium Corporation; Canadian Copper Refiners, Limited; Chemical Commerce; W. H. Curtin and Company; Delta Chemical Works, Inc.; E. I. DuPont de Nemours and Co.; Fairmount Chemical Co., Inc.; Harshaw Scientific; International Selling Corp.; Kawecki Chemical Co.; Linde Co.; Lindsay Chemical Co.; Mallinckrodt Chemical Works; Matheson Coleman and Bell; Merck and Co., Inc.; Pennsylvania Salt Manufacturing Company; Pfaltz and Bauer, Inc.; Research Chemicals, Inc.; Sylvania Electric Products, Inc.; Vanadium Corporation of America

and stability and Gorenbein's (1956) treatment of the electromotive series in sulfide paragenesis.

Electronegativity

Pritchard and Skinner (1955, p. 767) have reviewed the electronegativity numbers of Pauling (1948a, p. 58–75), Gordy (1946a; 1946b), and Haissinsky (1946). The series and graph chosen for Table 2 are taken from Povarennykh (1956b, p. 994) and are in terms of kilocalories per gram atom. In some cases Povarennykh's values are in disagreement with Haissinsky's, but in these cases, such as for Au^{+3} and Cu^{+1}, Pritchard and Skinner show discordances among the authors they cite. In such cases, Povarennykh's values are retained. Where Povarennykh gives no data, as for example, for Pd, Ru^{+3}, Ir, and Rh, these elements (without values) are interpolated into Povarennykh's series on basis of comparison with Pritchard and Skinner's compilation. Professor A. S. Povarennykh graciously forwarded corrected and new electronegativity values included in Table 2. These numbers are detailed in a forthcoming work (Povarennykh, in press). Application of electronegativity to geochemical problems is discussed by Chapman (1954), Fyfe (1951), and Ringwood (1955a). Bykov (1957) relates electronegativity to bond types.

Cation-Field Intensities

This series, from Dietzel (1942, p. 11), is applied by Osborn (1950, p. 221) and compared with lattice-energy coefficients by Leutwein and Doerffel (1956, p. 77).

Index of Ionic Replacement

The index of ionic replacement, or the index of diadochy as it is called in the original reference (Hori, 1954, p. 116–117), is a measure of the contribution of an interchangeable cation to the bond energy of a crystal. The index (D) depends upon the electrovalency, ionic radius, co-ordination and electronic configuration of the cation:

$$D = \frac{Z_m}{CR}\left(1 - \frac{1}{n}\right)$$

where

Z_m = electrovalency of the cation

C = presumed co-ordination number of cation

R = closest cation-anion distance under equilibrium conditions

n = Born exponent of repulsion

Indices of ionic replacement of the cations which are mutually replaceable are closest together. However, Hori (1954, p. 119–123) lists five cautions in the use of the indices which should be consulted by those who use them.

Another index (H) originated by Vendel (1955; 1958a; 1958b) is designed to serve the same purpose as Hori's index and is expressed:

$$H = r_n^3/r_k^3 \times I_n/I_k \times E_n/E_k$$

where r is the ionic radius; I is the ionization energy, E is the electronegativity, and n and k refer to the larger and smaller ion respectively.

Hydroxide Precipitation pH's

These data are derived from Britton (1956, p. 102). The uncertainty of position of Hg^{+2} should be noted. Bennett (1934, p. 573) finds that Hg^{+2} precipitates slightly above a pH of 4. The pH's of the natural media, quoted from Mason (1958, p. 158), also have considerable range and for most should not be quoted to the tenth of a unit.

Solubility of Sulfides

Otherwise known as the Schürmann series (Schürmann, 1888), this sequence is taken from Lindgren (1933, p. 826).

Affinity for Sulfur in Melt

This series, the Fournet and Schütz series is quoted from Rankama and Sahama (1950, p. 696).

Zoning

This sequence, which pertains to sulfide ores, has been modified from that cited in Rankama and Sahama (1950, p. 183) by the addition of stability factors taken from Barnes (in press). Stability factors are calculated values based on free energies which are a measure of the difference between the ionization potential of the neutral atom and the heat of hydration of the corresponding ion. These factors form a series of decreasing stability for metal complexes with the same covalent-bond characteristics (Yatsimirskiĭ, 1951). Barnes, taking free ener-

gies from Latimer (1952), has recomputed these stability factors for the various metals shown with an arbitrary constant of 200 added to eliminate negative numbers. McKinstry and Kennedy (1957), A. B. Edwards (1954, p. 136–137), and Park (1955) offer comprehensive resumés on the subject of zoning.

Reaction

Bowen's reaction series is reproduced as modified by Eckermann (1944, p. 286). Relative lattice energies (times 10^3) are added to this series from Leutwein and Doerffel (1956, p. 93) to illustrate the anomalous results obtained with lattice energies in compounds involving aluminum in both fourfold and sixfold co-ordination. However, if we recognize this double role of aluminum and other amphoteric elements, the lattice-energy concept remains of considerable value relative to interpretation of geochemical processes.

Exchangeability in Clay Minerals

Grim (1953, p. 144–145) cites the data used in this series. The position of ammonium varies depending upon cations involved, kind of clay material, and experimental conditions. There is no single, universal replaceability series.

A series not indicated on Table 2 is that of filtration effect, discussed by Ovchinnikov (1956). Under unit pressure, the percentage of material filtered depends upon the porosity of the filtering medium, the temperature, and the radius of hydrated ion. Hydrated-ion radii from Ovchinnikov (1956) are indicated in Table 2 under Miscellaneous Radii with a subscript of *H*. At 1 atmosphere pressure and room temperature, the resulting series in order of increasing filtration effect (in parentheses) is: K^{+1} (6.0); Na^{+1} (7.0); Cu^{+2} (16.0); Zn^{+2} (17.0); Mg^{+2} (19.0); Co^{+2} (18.0). At 8 atmospheres pressure it is: Na^{+1} (16.0); Ca^{+2} (43.0). The importance of this effect in natural processes is that under certain conditions of temperature, pressure, concentration, and pore size, rocks can exhibit practically complete impermeability for certain dissolved materials and thereby serve as a natural barrier for such materials.

Ionic Potential and Co-ordination

Finally, all cations and positively charged anions are plotted on an ionic radius *versus* charge diagram with the resulting threefold classification shown. Szádeczky-Kardoss (1955a, p. 118) provides an extension of this diagram to include the negatively charged ions. His general classification of sediments superposed on this extended plot has been criticized by Leutwein and Doerffel (1956, p. 85). The diagram shown in Table 2 is amplified by Noll (1931, p. 557), Goldschmidt (1934), and Wickman (1944).

In the graph of co-ordination versus charge, the packing percentages have been taken from Holser (1956) modified from A. F. Wells (1954).

Techniques and Trends in Geochemistry

Many of the pre-1953 geochemical data are now obsolete. Implicit in this growth of geochemistry are the diverse needs of modern technology. There is demand for such obscure information as the know-how of preparation of spherical clay particles containing radioactive ions (Ginnell and Simon, 1952) or even mineral analysis of air pollutants (Willy, 1954). The earth scientist is becoming more closely associated with the statistician, the chemist, the physicist, the electronic engineer, and the metallurgist.

One aspect of the technological bloom in progress is the development of techniques to obtain chemical data by remote control. In this connection we might note the budding of bore-hole spectroscopy (Khristianov, Panov, and Chernova, 1957; Muench and Osoba, 1957; A. Youmans and J. H. Buck, 1957; Baker, 1957; Caldwell and Sippel, 1958; P. W. Martin 1956, unpublished paper No. 657-G, An Atom Smasher for Well Logging, presented at a joint meeting of Rocky Mountain Petroleum Sections, Am. Inst. of Mining and Metallurgical Engineers, May 17–18, 1956). Detection of many of the major elements and promise of detection of some minor elements are possible by use of downhole nuclear devices. The prognosis is good for the blending of nuclear physics and the earth sciences (Johnson, 1950; Boganik, 1953).

In the scramble for instrumental prowess, geologic analysis and synthesis of data obtained from rocks and minerals by remote-control devices should not be minimized. Poorly or improperly selected or processed earth materials may yield nonrealistic results in nuclear geochemical research.

Another promising trend is derivation of

chemical data from physical or optical properties of rocks and minerals (Frietsch, 1957; Sun and Baldwin, 1954; Savintsev, 1956; W. R. Brode, 1955; Takano, 1957; Henriques, 1957; Sriramadas, 1957; Tabuko and Ukai, 1952). Correlation of such properties as optical reactivity with iron or magnesium content has been demonstrated by Vistelius (1956). Machine computation will materially aid such studies in the future.

Other techniques, some new, some revitalized, are coming to the fore. It is encouraging to note that many spectra or patterns of earth materials displayed by new instruments are being published. Comparison of these spectra by those familiar with the origin and processing of the sample may reveal much more than an analog-computed correlation coefficient.

A selected list of a few of these techniques and a very limited selection of references includes:

Natural isotope tracer and dilution techniques	Craig (1953)
Emission spectroscopy	Ahrens (1957c)
Ion exchange-spectrochemical	Edge *et al.* (1959)
Electron microscopy	R. B. Fischer (1953); Gritsaenko (1956)
Differential thermal analysis	Stone (1951); Smothers and Chiang (1958)
Neutron activation	Goldberg and Brown (1949)
Electron-probe microanalysis	Castaing and Fredriksson (1958)
Neutron diffractometry	Busing and Levy (1958)
Proton-resonance spectrometry	Spence and Muller (1958)
Thermoluminescence	Daniels and Saunders (undated)
Electrodialysis	Ivanov and Sheina (1956)
Flame photometry	Beck (1957)
Mass spectroscopy	Ubisch (1953)
X-ray spectroscopy	Adler and Axelrod (1955)
Gamma-ray spectroscopy	Heath (1957)
Electron paramagnetic spectroscopy	Hurd, Sachs, and Hershberger (1953); Bleaney, Llewellyn, and Jones (1956)
Infrared spectroscopy	Stubican (1957); Rudnitskaya (1956)
Near infrared	S. P. Clark, Jr. (1957); Roy and Roy (1957)

Summaries of many of these methods may be found in recent texts such as Berl (1956), or particularly, Yoe and Koch (1957).

This geochemical table of the elements for 1959 will soon be out of date. However, such a compilation, albeit limited in scope and subject to oversimplification, pinpoints areas for further geochemical research. Such research could be more conveniently implemented if there were one system of atomic weights, one system for representing elemental abundances, one system for normalizing selected sets of ionic sizes or energy coefficients, or one system of interlaboratory analytical techniques.

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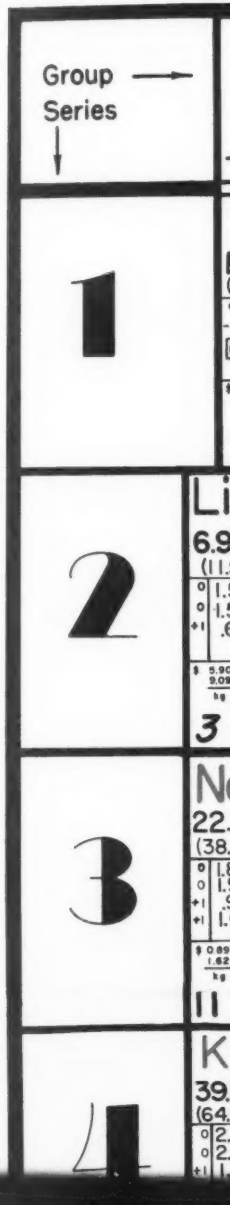
AERO-SPACE LABORATORIES, NORTH AMERICAN AVIATION, MISSILE DIVISION, DOWNEY, CALIFORNIA

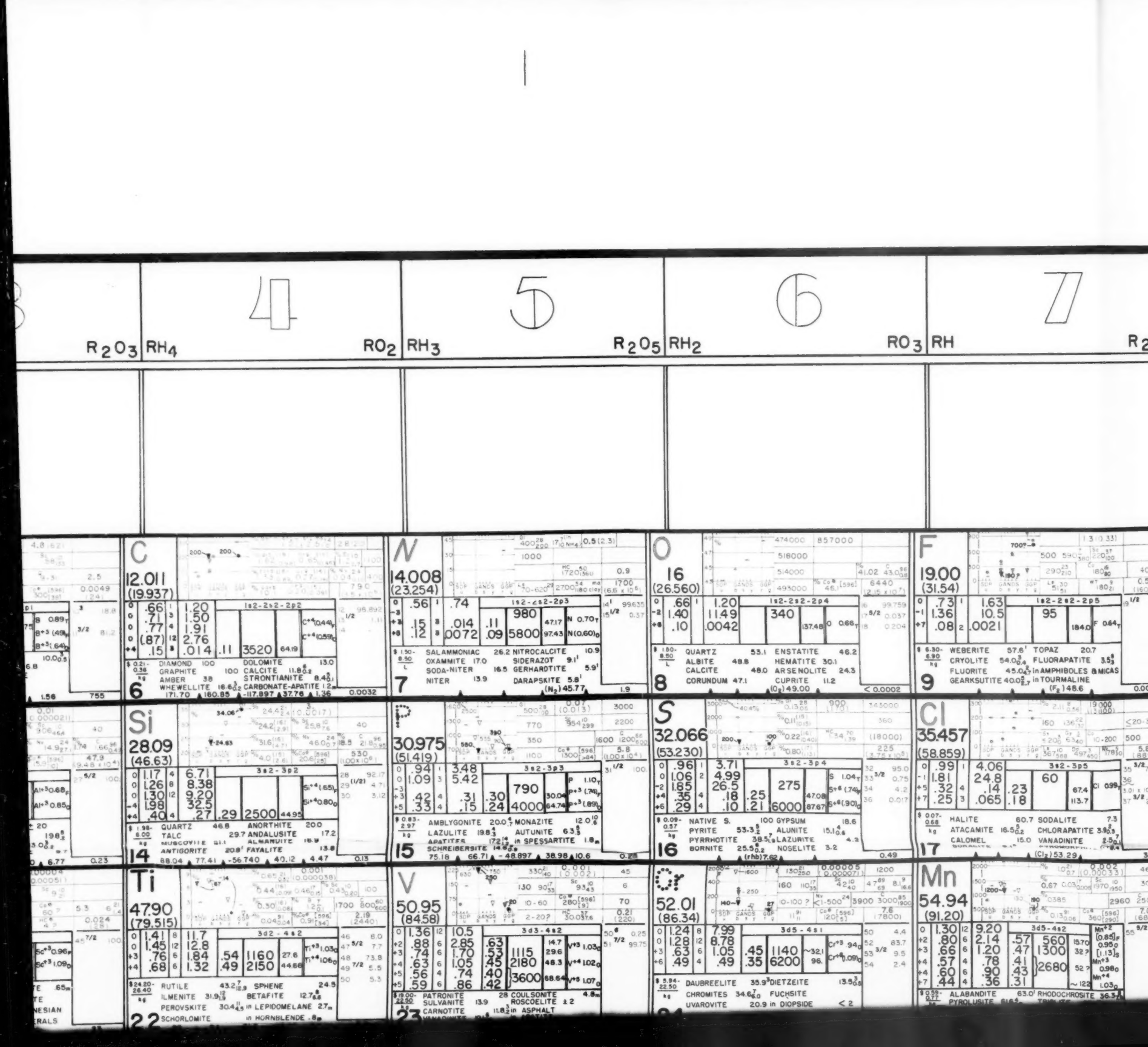
MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, JULY 2, 1958

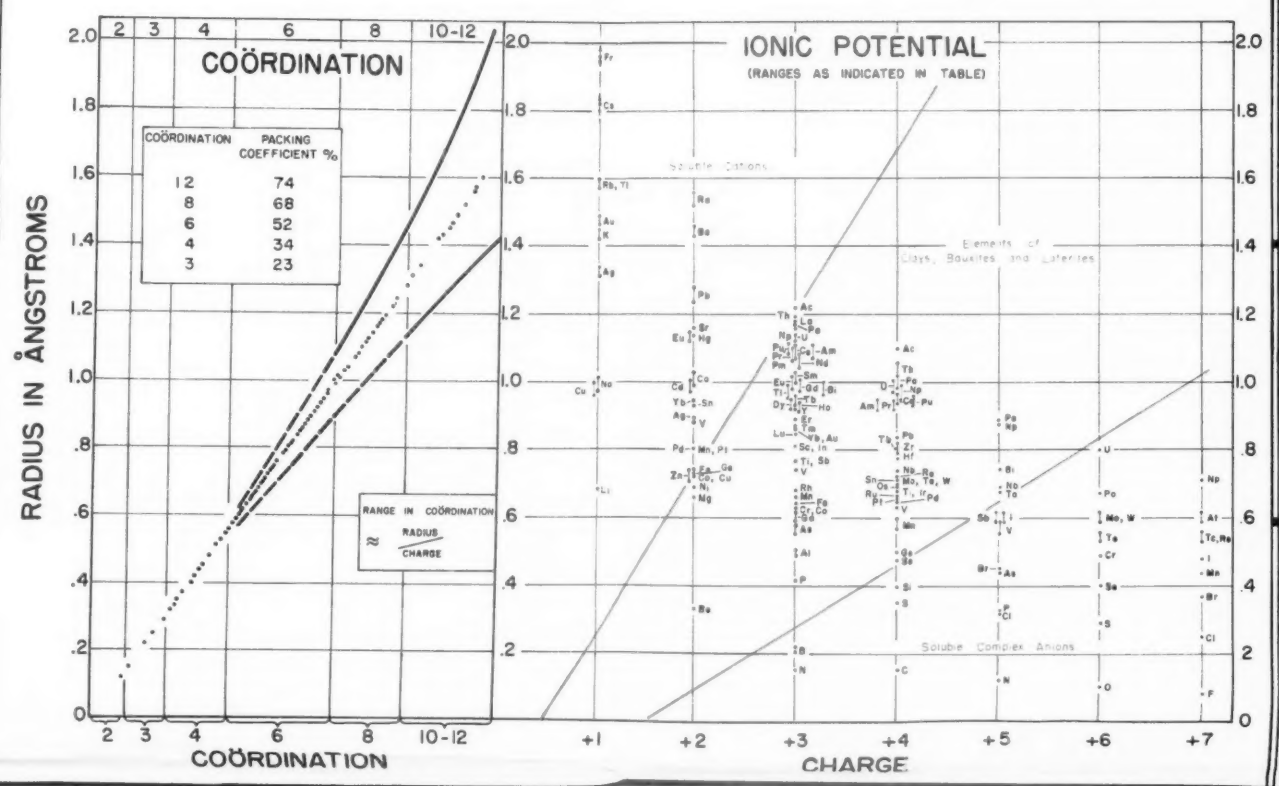
ACTINIUM	Ac	89
Actinium A (AcA) - Po^{215}		
Actinium B (AcB) - Pb^{211}		
Actinium C (AcC) - Bi^{211}		
Actinium C' (AcC') - Po^{211} (metastable)		
Actinium C'' (AcC'') - Tl^{207}		
Actinium D (AcD) - Pb^{207}		
Actinium K (AcK) - Fr^{223}		
Actinium X (AcX) - Ra^{223}		
Actinon (An) - Rn^{219}		
Actinouranium (AcU) - U^{235}		
Alabamine - astatine		
Aldebaranium - ytterbium		
Aluminium - aluminum		
ALUMINUM	Al	13
AMERICIUM	Am	95
ANTIMONY	Sb	51
Argentum - Silver		
ARGON	Ar	18
ARSENIC	As	33
ASTATINE	At	85
Aurum - gold		
Austrium - impure gallium		
BARIUM	Ba	56
BERKELIUM	Bk	97
BERYLLIUM	Be	4
BISMUTH	Bi	83
BORON	B	5
Brevium - Pa ^{234}		
BROMINE	Br	35
CADMIUM	Cd	48
CALCIUM	Ca	20
CALIFORNIUM	Cf	98
CARBON	C	6
Casseopeum (Cp) - lutetium		
Celtium - lutetium		
CERIUM	Ce	58
CESIUM	Cs	55
CHLORINE	Cl	17
CHROMIUM	Cr	24
COBALT	Co	27
Columbium - niobium		
COPPER	Cu	29
Coronium - hypothetical solar element		
CURIUM	Cm	96
Cyclonium - promethium		
Demonium - dysprosium		
Deuterium (D) - H^2		
Didymium - neodymium and praseodymium		
Dvitellurium - polonium		
Dwi-manganese - rhenium		
DYSPROSIUM	Dy	66
EINSTEINIUM	Es	99
MENDELEVIUM	Md	101
MERCURY	Hg	80
Mesothorium$_1$ ($MsTh_1$) - Ra^{228}		
Mesothorium$_2$ ($MsTh_2$) - Ac^{228}		
MOLYBDENUM	Mo	42
Natrium - sodium		
Nebulium - hypothetical cosmic element		
NEODYMIUM	Nd	60
Neoytterbium - ytterbium		
NEPTUNIUM	Np	93
NEON	Ne	10
NICKEL	Ni	28
NIOBIUM	Nb	41
Nipponium (obsolete) - Re + Mo oxides (?)		
Niton - radon		
NITROGEN	N	7
NOBELIUM	No	102
OSMIUM	Os	76
OXYGEN	O	8
PALLADIUM	Pd	46
PHOSPHORUS	P	15
PLATINUM	Pt	78
Plumbum - lead		
PLUTONIUM	Pu	94
POLONIUM	Po	84
POTASSIUM	K	19
PRASEODYMIUM	Pr	59
PROMETHIUM	Pm	61
PROTACTINIUM	Pa	91
Radioactinium (RdAc) - Th^{227}		
Radiothorium (RdTh) - Th^{228}		
RADIUM	Ra	88
Radium A (RaA) - Po^{218}		
Radium B (RaB) - Pb^{214}		
Radium C (RaC) - Bi^{214}		
Radium C' (RaC') - Po^{214}		
Radium C'' (RaC'') - Tl^{210}		
Radium D (RaD) - Pb^{210}		
Radium E (RaE) - Bi^{210}		
Radium E'' (RaE'') - Tl^{206}		
Radium emanation - radon		
Radium F (RaF) - Po^{210}		
Radium G (RaG) - Pb^{206}		
RADON	Rn	86
RHENIUM	Re	75
RHODIUM	Rh	45
RUBIDIUM	Rb	37
RUTHENIUM	Ru	44
SAMARIUM	Sm	62
SCANDIUM	Sc	21
SELENIUM	Se	34
SILICON	Si	14
SILVER	Ag	47
SODIUM	Na	11



oup → ries	1 — R_2O	2 — RO	3 — R_2O_3	4 RH_4 — RO_2	R
1	**H** 1.0080 (1.6733)				
2	**Li** 6.940 (11.52)	**Be** 9.013 (14.96)	**B** 10.82 (17.96)	**C** 12.011 (19.937)	**N** 14.0 (23.2
3	**Na** 22.991 (38.165)	**Mg** 24.32 (40.37)	**Al** 26.98 (44.79)	**Si** 28.09 (46.63)	30 (51.
4	**K** 39.100 (64.907)	**Ca** 40.08 (66.534)	**Sc** 44.96 (74.634)	**Ti** 47.90 (79.515)	V 50 (8

H of structural water in hydrous minerals
WATER 11.2 ANTIGORITE 1.4
CHALCANTHITE 4.0 HYDROZINCITE 1.1
MONTMORILLONITE 2.6 ANALCITE 0.9
GYPSUM 2.3 MUSCOVITE 0.5
AMBLYGONITE 3.9 LEPIDOLITE ±2
TRIPHYLITE 3.9 in HECTORITE .46
SPODUMENE 3.9 in PYROBOLES
PETALITE 2.3 in GLAUCONITE .035
HALITE 39.3 MIRABILITE 14.1
CRYOLITE 32.5 NATROLITE 12.1
SODALITE 19.0 BORAX 12.0
NEPHELINITE 14.4 ALBITE 8.8
PHENAKITE 16.4 BERYL 3.7 - 5.5
BERYLLONITE 7.0 in ALLANITE 5.
CHRYSOBERYL 6.6 in ORANGITE <.01
EUCLASE 6.2 in THORITE
FORSTERITE 34.1 PYROPE 18.0
MAGNESITE 25.5 SPINEL 12.4
ANTIGORITE 25.0 DOLOMITE
ENSTATITE 24.0 EPSOMITE
CORUNDUM 52.6 MUSCOVITE ± 20
GIBBSITE 33.9 KAOLINITE 19
KYANITE 33.3 CRYOLITE 13.0
TOPAZ 29.3 ORTHOCLASE
COLEMANITE 15.7 SUSSEXITE 10.0
SASSOLITE 17.5 DATOLITE 6.8
ULEXITE 13.3 TOURMALINE
BORAX 11.4 AXINITE
DIAMOND 100 DOLOMITE 13.0
GRAPHITE 100 CALCITE 11.8
AMBER 38 STRONTIANITE 8.4
WHEWELLITE 16.6 CARBONATE-APATITE 12
QUARTZ 46.8 ANORTHITE 20.0
TALC 29.7 ANDALUSITE 17.2
MUSCOVITE 9.1 ALMANDITE 16.9
ANTIGORITE 20.8 FAYALITE 13.8


4
5
6
7
R2O3
RH4
RO2
RH3
R2O5
RH2
RO3
RH
R2
C
12.011
(19.937)
DIAMOND 100
GRAPHITE 100
AMBER 38
WHEWELLITE 16.6
171.70 ▲ 160.85 ▲ -117.897 ▲ 37.76 ▲ 1.36
DOLOMITE 13.0
CALCITE 11.8
STRONTIANITE 8.4
CARBONATE-APATITE 1.2
6
0.0032
N
14.008
(23.254)
SALAMMONIAC 26.2
OXAMMITE 17.0
SODA-NITER 16.5
NITER 13.9
NITROCALCITE 10.9
SIDERAZOT 9.1
GERHARDTITE 5.9
DARAPSKITE 5.8
(N2) 45.77
7
1.9
O
16
(26.560)
QUARTZ 53.1
ALBITE 48.8
CALCITE 48.0
CORUNDUM 47.1
ENSTATITE 46.2
HEMATITE 30.1
ARSENOLITE 24.3
CUPRITE 11.2
(O2) 49.00
8
< 0.0002
F
19.00
(31.54)
WEBERITE 57.6
CRYOLITE 54.0
FLUORITE 45.0
GEARKSUTITE 40.0
TOPAZ 20.7
FLUORAPATITE 3.5
in AMPHIBOLES & MICAS
in TOURMALINE
(F2) 48.6
9
Si
28.09
(46.63)
QUARTZ 46.8
TALC 29.7
MUSCOVITE 21.1
ANTIGORITE 20.8
ANORTHITE 20.0
ANDALUSITE 17.2
ALMANDITE 16.9
FAYALITE 13.8
88.04 ▲ 77.41 ▲ -56.740 ▲ 40.12 ▲ 4.47
14
0.13
P
30.975
(51.419)
AMBLYGONITE 20.0
LAZULITE 19.8
APATITES 17.2
SCHREIBERSITE 14.6
MONAZITE 12.0
AUTUNITE 6.3
in SPESSARTITE 1.8
75.18 ▲ 66.71 ▲ -48.897 ▲ 38.98 ▲ 10.6
15
0.25
S
32.066
(53.230)
NATIVE S. 100
PYRITE 53.3
PYRRHOTITE 38.5
BORNITE 25.5
GYPSUM 18.6
ALUNITE 15.1
LAZURITE 4.2
NOSELITE 3.2
(rhb) 7.62
16
0.49
Cl
35.457
(58.859)
HALITE 60.7
ATACAMITE 16.5
CALOMEL 15.0
SODALITE 7.3
CHLORAPATITE 3.9
VANADINITE 2.5
(Cl2) 53.29
17
Ti
47.90
(79.515)
RUTILE 43.2
ILMENITE 31.9
PEROVSKITE 30.4
SPHENE 24.9
BETAFITE 12.7
in LEPIDOMELANE 2.7
in HORNBLENDE .8
SCHORLOMITE
22
V
50.95
(84.58)
PATRONITE 28
SULVANITE 13.9
CARNOTITE 11.8
COULSONITE 4.8
ROSCOELITE ± 2
in ASPHALT
23
Mn
54.94
(91.20)
ALABANDITE 63.0
PYROLUSITE 63.2
RHODOCHROSITE 36.3



He 4.003 (6.645)
1.45 | 12.8 | 1s2 | 1/2
$ 1.50-8.50/L
in BERYL 30 ppm | in SPODUMENE
in HALITE | in THORIANITE
in MAGNETITE | in SPHENE
in MONAZITE | in ZIRCON
2 | 30.13

Ne 20.183 (33.504)
1.52 | 12 | 14.7 | 1s2 - 2s2 - 2p6 | ±1/2
$ 1.50-8.50/L
10 | 34.95

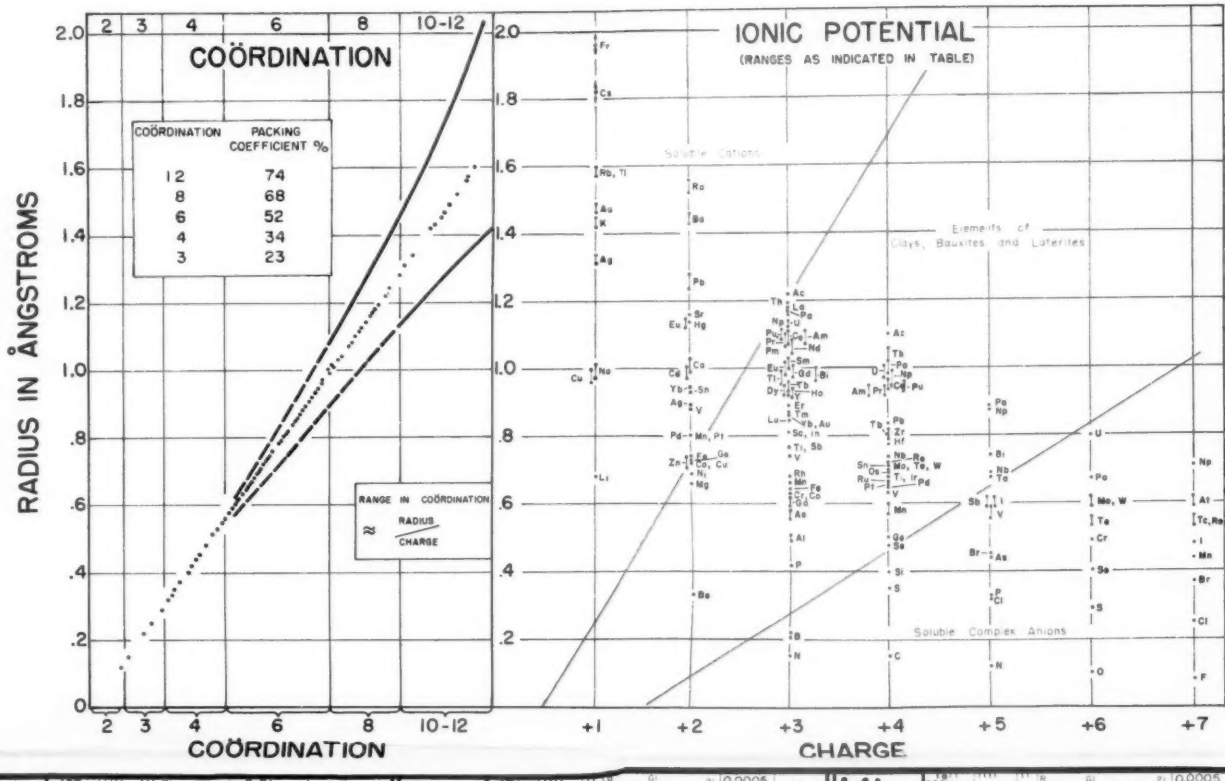
Ar 39.944 (66.308)
1.91 | 29.2 | 3s2 - 3p6
$ 1.50-8.50/L
in GLAUCONITE | in SYLVITE
in MUSCOVITE | in ILLITE
in K FELDSPAR | in LEUCITE
18 | 36.98

Fe 55.85 (92.71)
0 1.24 8 | 7.99 | 3d6 - 4s2 | Fe+2 0.81F
0 1.27 12 | 8.58 | Fe+2 0.90O6
+2 .74 6 | 1.70 | .53 | 580 | 16.24 | Fe+3 1.10O6
+3 .64 6 | 1.10 | .46 | 1280 | Fe+3 0.81F | Fe+3 0.92O6
$ 1.33-1.73/kg NATIVE ter. Fe. 95 | PYRITE 44.1
HEMATITE 69.9 | SIDERITE 38.0

Co 58.94 (97.84)
0 1.22 8 | 7.61 | 3d7 - 4s2 | Co+2 0.82F
0 1.26 12 | 8.38 | Co+2 0.90O6
+2 .72 6 | 1.56 | .51 | 620 | 17.3 | Co+3 1.10O6
+3 .63 6 | 1.05 | .45 | 1320 | Co+3 3.65H
$ 1.75-2.55/kg COBALTOCALCITE 45.7 | BIEBERITE 17.0
LINNAEITE 44.7 | SKUTTERUDITE 11.3

Ni 58.71 (97.46)
0 1.21 8 | 7.42 | 3d8 - 4s2 | Ni+2 [0.80]F
0 1.24 12 | 7.99 | Ni+2 0.91O6
+2 .69 6 | 1.38 | .49 | 620 | 18.13 | Ni+2 1.11H
$ 0.72-2.08/kg ter. NICKEL-IRON 74.2 | TREVORITE 23.3
MILLERITE 64.7 | ANNABERGITE 20.7

	7	8
RO_3 | RH		R_2O_7



F 19.00 (31.54)

0	.73	1	1.63	1s2-2s2-2p5				
-1	1.36		10.5		95		184.0	F 0.64
+7	.08	2	.0021					

WEBERITE 57.6 TOPAZ 20.7
CRYOLITE 54.0 FLUORAPATITE 3.5
FLUORITE 45.0 in AMPHIBOLES & MICAS
GEARKSUTITE 40.0 in TOURMALINE
(F_2) 48.6

9

Cl 35.457 (58.859)

0	.99	1	4.06	3s2-3p5				
-1	1.81		24.8		60		67.4	Cl 0.99
+5	.32	4	.14	.23				
+7	.25	3	.065	.18			113.7	

HALITE 60.7 SODALITE 7.3
ATACAMITE 16.5 CHLORAPATITE 3.9
CALOMEL 15.0 VANADINITE 2.5

17

Mn 54.94 (91.20)

0	1.30	12	9.20	3d5-4s2				
+2	.80	6	2.14	.57	560		15.70	Mn^{+2} [0.85]F 0.95Q
+3	.66	6	1.20	.47	1300		32?	[1.13]S
+4	.57	4	.78	.41	2680		52?	Mn^{+3} 0.98Q
+6	.60	6	.90	.43				Mn^{+4}
+7	.44	4	.36	.31				

Fe 55.85 (92.71)

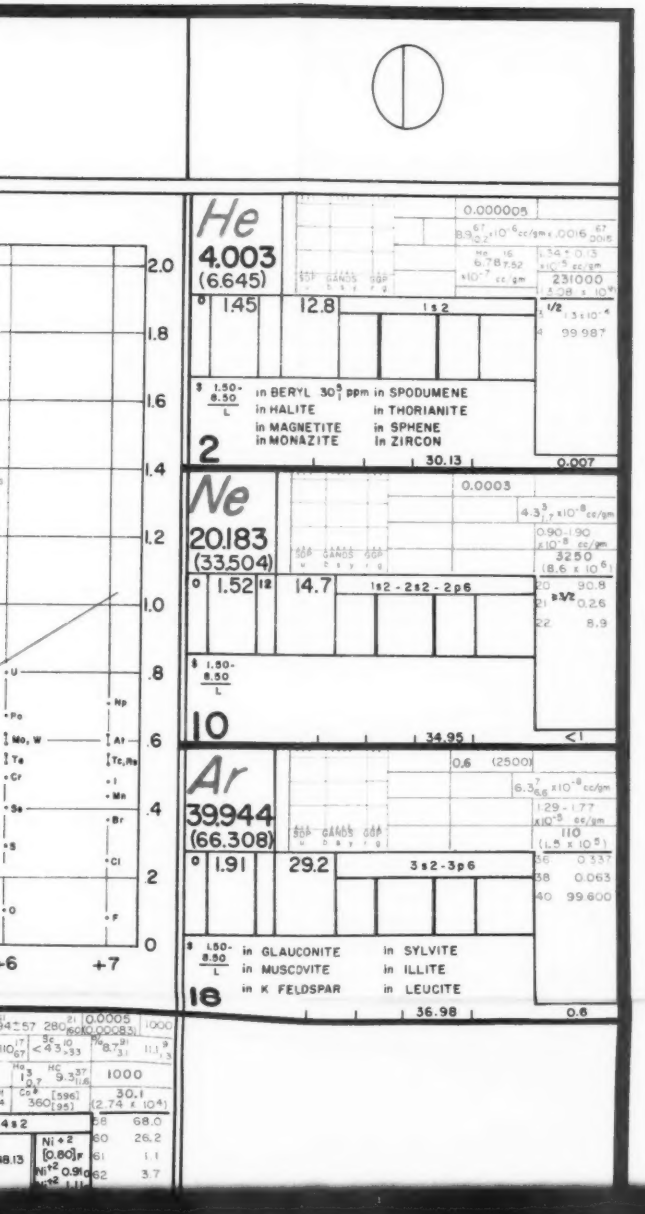
0	1.24	8	7.99	3d6-4s2				
0	1.27	12	8.58					
+2	.74	6	1.70	.53	580	16.24		Fe^{+2} 0.81F
+3	.64	6	1.10	.46	1280			Fe^{+2} 0.90Q
								Fe^{+2} 1.10S
								Fe^{+3} 0.81F
								Fe^{+3} 0.92Q

Co 58.94 (97.84)

0	1.22	8	7.61	3d7-4s2				
0	1.26	12	8.38					
+2	.72	6	1.56	.51	620	17.3		Co^{+2} 0.82F
+3	.63	6	1.05	.45	1320			Co^{+2} 0.90Q
								Co^{+2} 1.10S
								Co^{+3} 3.65H

Ni 58.71 (97.46)

0	1.21	8	7.42	3d8-4s2				
0	1.24	12	7.99					
+2	.69	6	1.38	.49	620	18.13		Ni +2 [0.80]F
								Ni^{+2} 0.91Q
								Ni^{+2} 1.11



SERIES

ELECTROMOTIVE

Standard electrode potentials at 25°C

$Li^{+1} + e_0^- \rightleftharpoons Li$	−3.01 ± icv	$Cu^{+2} + 2e_0^- \rightleftharpoons Cu$	+0.34 ± icv
$Rb^{+1} + e_0^- \rightleftharpoons Rb$	−2.98 ± icv	$\frac{1}{2}O_2 + H_2O + 2e_0^- \rightleftharpoons 2OH^-$	+0.401 ± imv
$Cs^{+1} + e_0^- \rightleftharpoons Cs$	−2.92 ± icv	$Cu^{+1} + e_0^- \rightleftharpoons Cu$	+0.52 ± icv
$K^{+1} + e_0^- \rightleftharpoons K$	−2.92 ± icv	$I_2 + 2e_0^- \rightleftharpoons 2I^-$	+0.536 ± imv
$Ba^{+2} + 2e_0^- \rightleftharpoons Ba$	−2.92 ± icv	$Te^{+4} + 4e_0^- \rightleftharpoons Te$	+0.56 ± icv
$Sr^{+2} + 2e_0^- \rightleftharpoons Sr$	−2.89 ± icv	$Po^{+3} + 3e_0^- \rightleftharpoons Po$	+0.56 ± ?v
$Ca^{+2} + 2e_0^- \rightleftharpoons Ca$	−2.84 ± icv	$Rh^{+2} + 2e_0^- \rightleftharpoons Rh$	+0.6 ± ?v
$Na^{+1} + e_0^- \rightleftharpoons Na$	−2.713 ± imv	$Hg_2^{+2} + 2e_0^- \rightleftharpoons 2Hg$	+0.798 ± imv
$La^{+3} + 3e_0^- \rightleftharpoons La$	−2.4 ± ?v	$Ag^{+1} + e_0^- \rightleftharpoons Ag$	+0.799 ± imv
$Mg^{+2} + 2e_0^- \rightleftharpoons Mg$	−2.38 ± icv	$Pd^{+2} + 2e_0^- \rightleftharpoons Pd$	+0.83 ± ?v
$Th^{+4} + 4e_0^- \rightleftharpoons Th$	−2.1 ± ?v	$Ir^{+3} + 3e_0^- \rightleftharpoons Ir$	+1.0 ± ?v
$Ti^{+2} + 2e_0^- \rightleftharpoons Ti$	−1.75 ± ?v	$Br_2(l) + 2e_0^- \rightleftharpoons 2Br^-$	+1.066 ± imv
$Be^{+2} + 2e_0^- \rightleftharpoons Be$	−1.70 ± icv	$Pt^{+2} + 2e_0^- \rightleftharpoons Pt$	+1.2 ± ?v
$Al^{+3} + 3e_0^- \rightleftharpoons Al$	−1.66 ± icv	$Cl_2 + 2e_0^- \rightleftharpoons 2Cl^-$	+1.358 ± imv
$V^{+2} + 2e_0^- \rightleftharpoons V$	−1.5 ± ?v	$Au^{+3} + 3e_0^- \rightleftharpoons Au$	+1.42 ± ?v
$Mn^{+2} + 2e_0^- \rightleftharpoons Mn$	−1.05 ± ?v	$Au^{+1} + e_0^- \rightleftharpoons Au$	+1.7 ± ?v
$Te + 2e_0^- \rightleftharpoons Te^{-2}$	−0.92 ± ?v	$F_2 + 2e_0^- \rightleftharpoons 2F^-$	+2.85 ± icv
$Se + 2e_0^- \rightleftharpoons Se^{-2}$	−0.78 ± icv		
$Zn^{+2} + 2e_0^- \rightleftharpoons Zn$	−0.763 ± imv		
$Cr^{+3} + 3e_0^- \rightleftharpoons Cr$	−0.71 ± ?v		
$Ga^{+3} + 3e_0^- \rightleftharpoons Ga$	−0.52 ± icv		
$S + 2e_0^- \rightleftharpoons S^{-2}$	−0.51 ± icv		
$Fe^{+2} + 2e_0^- \rightleftharpoons Fe$	−0.44 ± icv		
$Cd^{+2} + 2e_0^- \rightleftharpoons Cd$	−0.402 ± imv		
$In^{+3} + 3e_0^- \rightleftharpoons In$	−0.34 ± icv		
$Tl^{+1} + e_0^- \rightleftharpoons Tl$	−0.335 ± imv		
$Co^{+2} + 2e_0^- \rightleftharpoons Co$	−0.27 ± icv		
$Ni^{+2} + 2e_0^- \rightleftharpoons Ni$	−0.23 ± icv		
$Mo^{+3} + 3e_0^- \rightleftharpoons Mo$	−0.2 ± ?v		
$Sn^{+2} + 2e_0^- \rightleftharpoons Sn$	−0.140 ± imv		
$Pb^{+2} + 2e_0^- \rightleftharpoons Pb$	−0.126 ± imv		
$D^{+1} + e_0^- \rightleftharpoons \frac{1}{2}D_2$	−0.003 ± icv		

v = volts
cv = centivolts
mv = millivolts

STANDARD OXIDATION-REDUCTION POTENTIALS AT 25°C.

Reaction	e_0 volts
$Cr^{+3} + e_0^- \rightleftharpoons Cr^{+2}$	−0.41
$Ti^{+3} + e_0^- \rightleftharpoons Ti^{+2}$	−0.37 ± 0.01
$V^{+3} + e_0^- \rightleftharpoons V^{+2}$	−0.20
$Sn^{+4} + 2e_0^- \rightleftharpoons Sn^{+2}$	0.154 ± 0.001
$Cu^{+2} + e_0^- \rightleftharpoons Cu^{+1}$	0.167 ± 0.001
$I_3^{-1} + 2e_0^- \rightleftharpoons 3I^{-1}$	0.535
$Fe^{+3} + e_0^- \rightleftharpoons Fe^{+2}$	0.771 ± 0.0005
$2Hg^{+2} + 2e_0^- \rightleftharpoons Hg_2^{+2}$	0.905 ± 0.001
$Tl^{+3} + 2e_0^- \rightleftharpoons Tl^{+1}$	1.25
$Mn^{+3} + e_0^- \rightleftharpoons Mn^{+2}$	1.51
$Ce^{+4} + e_0^- \rightleftharpoons Ce^{+3}$	1.610 ± 0.001
$H_2O_2 + 2H^{+1} + 2e_0^- \rightleftharpoons 2H_2O$	1.77
$Co^{+3} + e_0^- \rightleftharpoons Co^{+2}$	1.842 ± 0.001

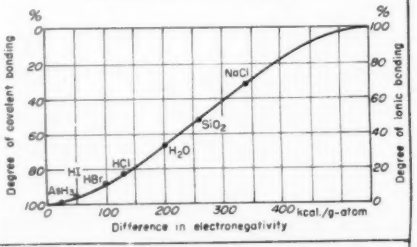
ELECTROCHEMICAL EQUIVALENTS

ELECTRONEGATIVITY

Kilocalories/gram-atom

Cs	89	Co^{+2}	200	Mn^{+3}	260
Rb	97	Sc	200	Co^{+3}	260
K	100	Zn	208	Ge	265
Ba	115	Be	210	Sb	270
Na	118	Ta^{+5}	(210)	Si	270
Sr	125	Au^{+1}	212	Pd	—
Li	125	Hg^{+2}	215	Mo^{+6}	275
Ca	137	Nb^{+4}	215	Ni^{+3}	275
Tl^{+1}	140	U^{+6}	(215)	V^{+4}	280
La	147	In	215	B	290
Ce^{+3}	160	As^{+3}	220	As^{+5}	310
Y	160	Ni^{+2}	220	Ru^{+3}	—
Th^{+4}	(170)	Ti^{+3}	220	Mn^{+4}	310
Pb^{+2}	170	Al	220	Ir	—
Mn^{+2}	170	Tl^{+3}	230	Rh	—
Mg	174	Ga	235	Te	315
Ag^{+1}	175	Cu^{+2}	235	V^{+5}	315
Cu^{+1}	177	V^{+3}	235	P	320
Hf^{+4}	(180)	Sn^{+4}	235	H	328
Fe^{+2}	185	W^{+6}	(235)	Se	360
Ta^{+4}	190	Nb^{+5}	240	Cr^{+6}	370
Ce^{+4}	190	Rh^{+3}	240	C	370
U^{+4}	(190)	Hg^{+1}	240	I	375
Bi^{+3}	195	Pt^{+4}	240	S	385
Sb^{+3}	195	Fe	245	Br	425
Cd	195	Pb	245	N	450
Pa^{+5}	(195)	Cr^{+3}	250	Cl	460
Pt^{+2}	200	Ti^{+4}	260	O	530
Zr	200	Re^{+7}	260	F	605

Extrapolated values in parentheses



INDEX OF IONIC REPLACEMENT

atomic number $= bA^{C}$ = charge

$_{55}Cs^{+1}$	.02	$_{30}Zn^{+2}$	.14	$_{27}Co^{+3}$	.22
$_{37}Rb^{+1}$	.03	$_{26}Fe^{+2}$	.14	$_{31}Ge^{+3}$	.22
$_{81}Tl^{+1}$	.03	$_{29}Cu^{+2}$	.14	$_{13}Al^{+3}$ (6 FOLD COORD.)	.23
$_{19}K^{+1}$	03	$_{27}Co^{+2}$	.14	$_{4}Be^{+2}$	.24
$_{47}Ag^{+1}$	.04	$_{50}Sn^{+2}$	.14	$_{72}Hf^{+4}$	.27
$_{11}Na^{+1}$	.06	$_{28}Ni^{+2}$	.14	$_{41}Nb^{+4}$	.28
$_{29}Cu^{+1}$	.06	$_{12}Mg^{+2}$	.14	$_{74}W^{+4}$	.28
$_{56}Ba^{+2}$	.07	$_{90}Th^{+4}$	.16	$_{42}Mo^{+4}$	.28

Columbium - niobium		
COPPER	Cu	29
Coronium - hypothetical solar element		
CURIUM	Cm	96
Cyclonium - promethium		
Demonium - dysprosium		
Deuterium (D) - H^2		
Didymium - neodymium and praseodymium		
Dvitellurium - polonium		
Dwi-manganese - rhenium		
DYSPROSIUM	Dy	66
EINSTEINIUM	Es	99
Eka-aluminum - gallium		
Eka-boron - scandium		
Eka-cesium - francium		
Eka-iodine - astatine		
Eka-manganese - technetium		
Eka-silicon - germanium		
Eka-tantalum - protactinium		
Emanation (Em) radon		
ERBIUM	Er	68
Erythronium - vanadium		
EUROPIUM	Eu	63
Ferrum - iron		
Florentium - promethium		
FERMIUM	Fm	100
FLUORINE	F	9
FRANCIUM	Fr	87
GADOLINIUM	Gd	64
GALLIUM	Ga	31
GERMANIUM	Ge	32
Glucin(i)um - beryllium		
GOLD	Au	79
HAFNIUM	Hf	72
HELIUM	He	2
HOLMIUM	Ho	67
Hydrargyrum - mercury		
HYDROGEN	H	1
Illinium - promethium		
INDIUM	In	49
IODINE	I	53
Ionium (Io) - Th^{230}		
IRIDIUM	Ir	77
IRON	Fe	26
Jod (J) - iodine		
Kalium - potassium		
KRYPTON	Kr	36
LANTHANUM	La	57
LEAD	Pb	82
LITHIUM	Li	3
Lutecium - lutetium		
LUTETIUM	Lu	71
MAGNESIUM	Mg	12
MANGANESE	Mn	25
Masurium - technetium		
Radium F (RaF) - Po^{210}		
Radium G (RaG) - Pb^{206}		
RADON	Rn	86
RHENIUM	Re	75
RHODIUM	Rh	45
RUBIDIUM	Rb	37
RUTHENIUM	Ru	44
SAMARIUM	Sm	62
SCANDIUM	Sc	21
SELENIUM	Se	34
SILICON	Si	14
SILVER	Ag	47
SODIUM	Na	11
Stannum - tin		
Stibium - antimony		
STRONTIUM	Sr	38
SULFUR	S	16
TANTALUM	Ta	73
TECHNETIUM	Tc	43
TELLURIUM	Te	52
TERBIUM	Tb	65
THALLIUM	Tl	81
THORIUM	Th	90
Thorium A (ThA) - Po^{216}		
Thorium B (ThB) - Pb^{212}		
Thorium C (ThC) - Bi^{212}		
Thorium C' (ThC') - Po^{212}		
Thorium C'' (ThC'') - Tl^{208}		
Thorium D (ThD) - Pb^{208}		
Thorium X (ThX) - Ra^{224}		
Thoron (Tn) - Rn^{220}		
THULIUM	Tm	69
TIN	Sn	50
TITANIUM	Ti	22
Tritium (T) - H^3		
TUNGSTEN	W	74
URANIUM	U	92
Uranium (I) - U (I) - U^{238}		
Uranium (II) - U (II) - U^{234}		
Uranium X_1 (UX_1) - Th^{234}		
Uranium X_2 (UX_2) - Pa^{234} metastable		
Uranium Y (UY) - Th^{231}		
Uranium Z (UZ) - Pa^{234}		
VANADIUM	V	23
Virginium - francium		
Wolfram - tungsten		
Wolframium - tungsten		
XENON	Xe	54
YTTERBIUM	Yb	70
YTTRIUM	Y	39
ZINC	Zn	30
ZIRCONIUM	Zr	40

élément
Element
elemento
элемент

poids atomique
Atomgewicht
peso atómico
атомный вес

le poids d'un atome × 10^{-24} grammes
Gewicht eines Atoms × 10^{-24} Gramm
el peso de un átomo × 10^{-24} gramos
вес одного атома × 10^{-24} граммов

abondances
Gehalte
abundancias
относительное содержание

gramme/tonne
Gramm/Tonne
gramo/tonelada
содержание в граммах на тонну

moyenne
arithmétique
Arithmetischer
Durchschnitt
promedio aritmético
среднее
арифметическое

A

b numéro de analyses
Anzahl der Analysen
número de analisis
количество анализов

c déviation normale
Normale Streuung
deviación normal
нормальное отклонение

▲ extrusif
extrusiv
extrusivo
эффузивные породы

● intrusif
intrusiv
intrusivo
интрузивные породы

types de roches ignées
Eruptivgesteinsarten
tipos de roca ignea
типы магматических пород

hydrolysate pélagique Meerhydrolysat hidrolizato pelágico глубоководные осадки	océan Ozean océano океан	sulfite météoritique Meteorsulfid sulfito meteorítico метеорный сульфид
argile schisteuse Schieferton lutita глинистый сланец	roches métamorphiques Metamorphes Gestein rocas metamórficas метаморфические породы	fer météoritique Meteoreisen hierro meteorítico метеорное железо
grès Sandstein arenisca песчаник	autre Andere otro другие	silicate météoritique Meteorsilikat silicato meteorítico метеорный силикат
carbonate Karbonat carbonato карбонат	autre Andere otro другие	univers Universum universo вселенная

charge Ladung carga заряд	rayon (Å) Radius radio радиус /Å/	coordination Koordination coordinación координационное число	volume Volumen volúmen объем

électrons dans chaque groupe quantum
Elektronen in jeder Quantumgruppe
electrones en cada grupo cuántico
число электронов в каждой квантовой группе

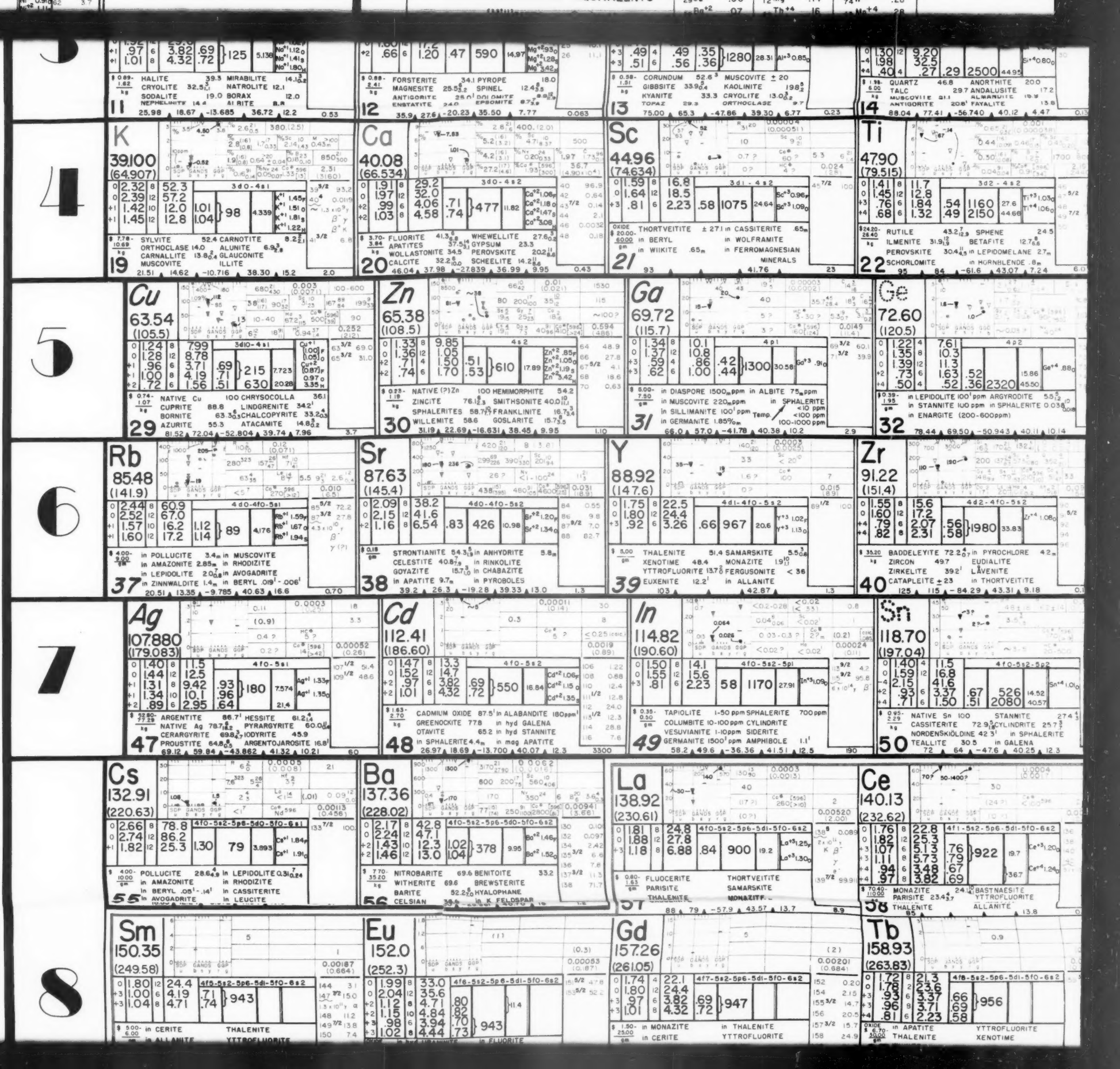
rapport des rayons Radius Verhältnis relación de los radios соотношение радиусов	coefficient d'énergie en treillis Gitterenergie-Koeffizient coeficiente de la energía de celosía коэффициент энергии кристаллической решетки	potentiel d'ionisation (volts) Ionisierungspotential (Volt) potencial de ionización (voltios) ионизационный потенциал /в вольтах/	rayons divers Verschiedene Radien radios diversos различные радиусы

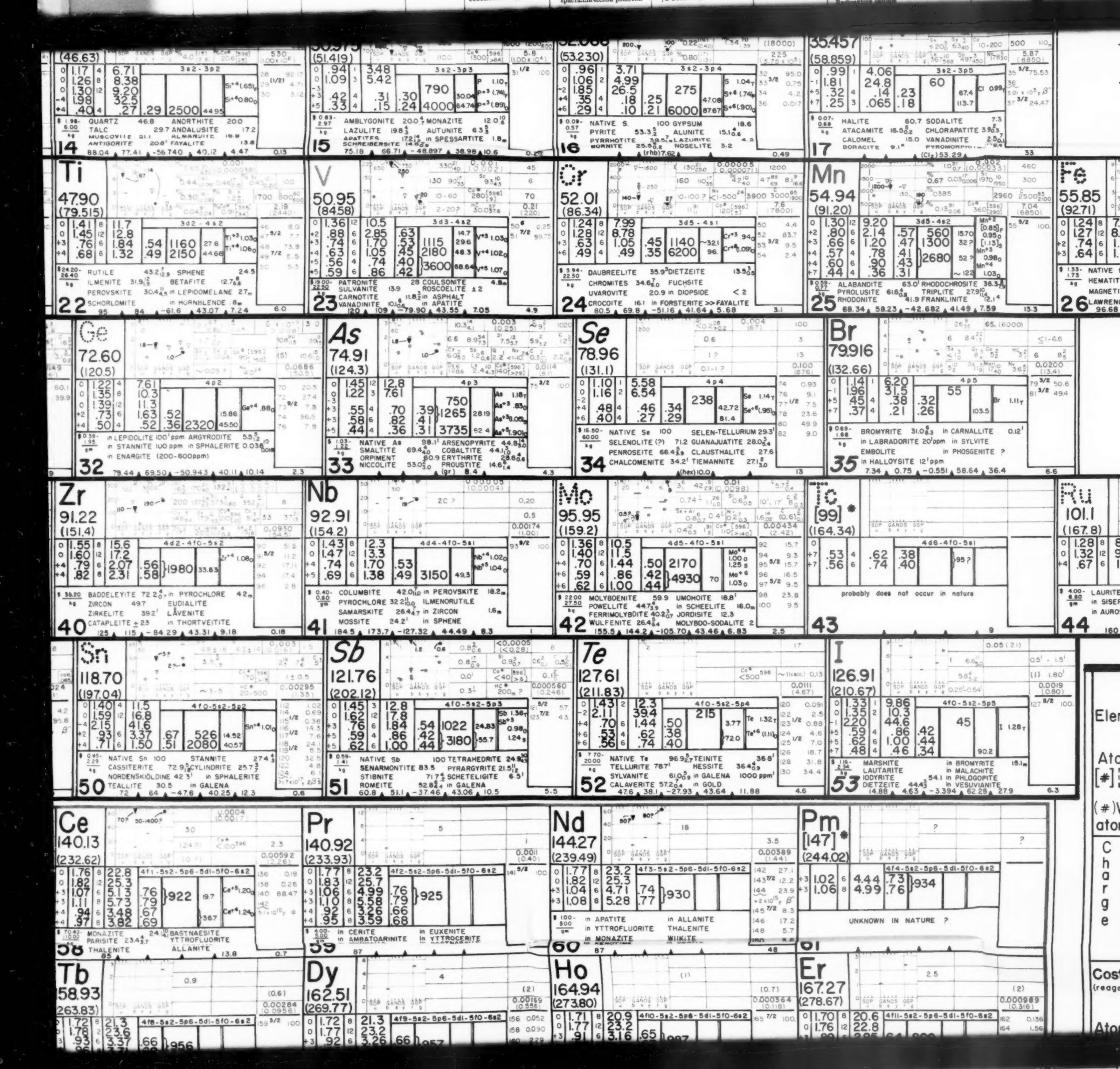
isotopes occurrent naturellement
Natürliche Isotope
isotopos que ocurren de una manera natural
изотопы, встречающиеся в природе

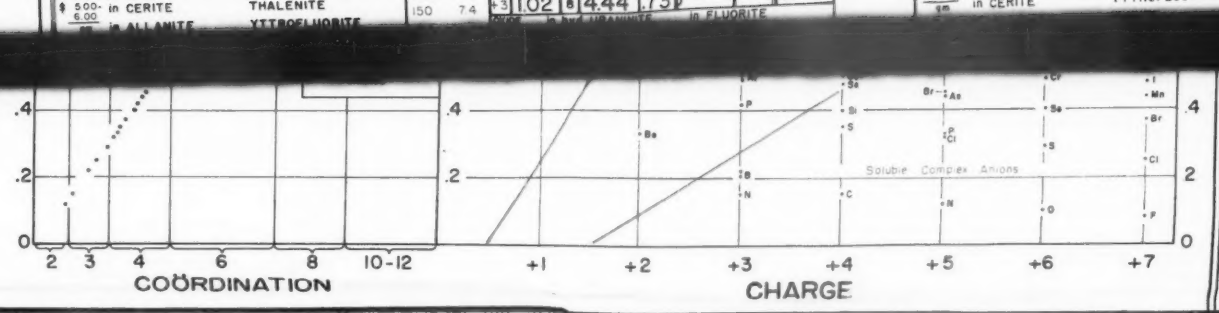
pour cent d'abondance relative
% relativer Gehalt
% de abundancia relativo
% относительного содержания

ressort nucléaire indiqué par suscript
Kernspin angedeutet durch Strich über dem betreffenden Zeichen
resorte nuclear indicado por superescrito
ядерный спин показан надстрочным индексом

isotope radio-actif


5
4
5
6
7
8
K 39.100 (64.907)
Ca 40.08 (66.534)
Sc 44.96 (74.634)
Ti 47.90 (79.515)
Cu 63.54 (105.5)
Zn 65.38 (108.5)
Ga 69.72 (115.7)
Ge 72.60 (120.5)
Rb 85.48 (141.9)
Sr 87.63 (145.4)
Y 88.92 (147.6)
Zr 91.22 (151.4)
Ag 107.880 (179.083)
Cd 112.41 (186.60)
In 114.82 (190.60)
Sn 118.70 (197.04)
Cs 132.91 (220.63)
Ba 137.36 (228.02)
La 138.92 (230.61)
Ce 140.13 (232.62)
Sm 150.35 (249.58)
Eu 152.0 (252.3)
Gd 157.26 (261.05)
Tb 158.93 (263.83)


Ti 47.90 (79.515)
V 50.95 (84.58)
Cr 52.01 (86.34)
Mn 54.94 (91.20)
Fe 55.85 (92.71)
Ge 72.60 (120.5)
As 74.91 (124.3)
Se 78.96 (131.1)
Br 79.916 (132.66)
Zr 91.22 (151.4)
Nb 92.91 (154.2)
Mo 95.95 (159.2)
Tc [99] (164.34)
Ru 101.1 (167.8)
Sn 118.70 (197.04)
Sb 121.76 (202.12)
Te 127.61 (211.83)
I 126.91 (210.67)
Ce 140.13 (232.62)
Pr 140.92 (233.93)
Nd 144.27 (239.49)
Pm [147] (244.02)
Tb 158.93 (263.83)
Dy 162.51 (269.77)
Ho 164.94 (273.80)
Er 167.27 (278.67)
probably does not occur in nature
UNKNOWN IN NATURE ?



Ar 39.944 (66.308)

0 | 1.91 | 29.2 | 3s2-3p6

$ 1.50-8.50/L — in GLAUCONITE, in MUSCOVITE, in K FELDSPAR; in SYLVITE, in ILLITE, in LEUCITE

18 — 36.98 — 0.6

Fe 55.85 (92.71)

0	1.24	8	7.99	3d6-4s2			Fe+2 0.81F	54	5.9
0	1.27	12	8.58				Fe+2 0.90O	56	91.6
+2	.74	6	1.70	.53	580	16.24	Fe+2 1.10S	57	2.2
+3	.64	6	1.10	.46	1280		Fe+3 0.81F	58	0.33
							Fe+3 0.92O		

$ 1.33-1.73/kg — NATIVE fer. Fe 95.1 4/2 PYRITE 44.1; HEMATITE 69.9 SIDERITE 35.0 7/8; MAGNETITE 63.3 5/3 JAROSITE 31.4 7/8

26 LAWRENCITE 44.1 GLAUCONITE ± 14

96.68 ▲ 85.76 -62.861 ▲ 43.11 ▲ 6.49 — 2.5

Co 58.94 (97.84)

0	1.22	8	7.61	3d7-4s2			Co+2 0.82F	59	7/2 100
0	1.26	12	8.38				Co+2 0.90O		
+2	.72	6	1.56	.51	620	17.3	Co+2 1.10S		
+3	.63	6	1.05	.45	1320		Co+3 3.65H		

$ 1.75-2.55/kg — COBALTOCALCITE 45.7 3/1.8 BIEBERITE 17.0 5/9; LINNAEITE 44.7 8/6.0 SKUTTERUDITE 11.3 11/21; COBALTITE 30.0 2/1.2 PYRITE < 1.3

27 ERYTHRITE 23.9 4/3.6 in SPHALERITE 0.3m

105 ▲ 94 -68.9 ▲ 42.88 ▲ 6.8 — 37

Ni 58.71 (97.46)

0	1.21	8	7.42	3d8-4s2				58	68.0
0	1.24	12	7.99					60	26.2
+2	.69	6	1.38	.49	620	18.13	Ni+2 [0.80]F	61	1.1
							Ni+2 0.91O	62	3.7
							Ni+2 1.11S	64	1.0

$ 0.72-2.08/kg — ter. NICKEL-IRON 74.2 2/3.8 TREVORITE 23.3; MILLERITE 64.7 ANNABERGITE 20.7 4/4.9; NICCOLITE 42.0 5/1.8 GARNIERITE

28 PENTLANDITE 34.6 4/3.3 CHLOANTHITE 17.9 2/4.7

101.61 ▲ 90.77 -66.533 ▲ 43.59 ▲ 7.20 — 4.6

Kr 83.80 (139.1)

0 | 2.0 | 33.5 | 4p6

$ 25.00-30.00/L

36 — 39.19 — 28

Ru 101.1 (167.8)

0	1.28	8	8.78	4d7-4f0-5s1				96	5.6
0	1.32	12	9.63					98	1.9
+4	.67	6	1.26	.48	2180		Ru+4 1.01O	99	5/2 12.7
								100	12.7
								101	5/2 17.0
								102	31.5
								104	18.6

$ 4.00-8.50/gm — LAURITE 61.1 in CHROMITE < .5 ppm; in SISERSKITE 11.1 2/2.4 in ILMENITE .004 ppm; in AUROSMIRIDIUM 3.5

44 160 ▲ 149 -109.2 ▲ 44.57 ▲ 6.9 — 2.5

Rh 102.91 (170.83)

0	1.30	8	9.20	4d8-4f0-5s1				103	1/2 100
0	1.34	12	10.1						
+3	.68	6	1.32	.49	1250		Rh+3 0.99O		

$ 5.00-8.00/gm — RHODITE in SPERRYLITE 1.7m; in SISERSKITE 11.3m in PLATINUM 0.6 8/1.6; in PLATINIRIDIUM 6.9m in CHROMITE 0.5 ppm

45 in IRIDOSMINE 4.5 in ALLOPALLADIUM

138 ▲ 127 -93.09 ▲ 44.39 ▲ 7.6 — 150

Pd 106.4 (176.6)

0	1.33	8	9.86	4d10				102	1.0
0	1.37	12	10.8					104	11.0
+2	.80	6	2.14	.57	640	19.8	Pd+2 .95F	105	5/2 22.2
+4	.65	6	1.15	.46			Pd+2 1.04O	106	27.3
							Pd+2 1.20S	108	26.7
								110	11.8

$ 2.50/gm — NATIVE Pd 100 BRAGGITE; STIBIOPALLADINITE PORPEZITE 10m; in PLATINUM 37.1m ALLOPALLADIUM; in CHROMITE 0.5 ppm in MOLYBDENITE

46 POTARITE

93 ▲ 84 -61.6 ▲ 39.91 ▲ 8.9 — 8

Xe 131.30 (217.96)

0 | 2.2 | 44.6 | 4f0-5s2-5p6

$ 30.00-55.00/l

54 — 40.53 — 35

KEY

Element
S - SIDEROPHILE
C - CHALCOPHILE
A - ATMOPHILE
L - LITHOPHILE
B - BIOPHILE and LITHOPHILE

Atomic Weight
[#] Mass of isotope of longest half life; [#]* - Mass of isotope of best known half life

(#) Weight of one atom x 10^{-24} grams

ABUNDANCES in ppm unless indicated otherwise (FOR SPECIFIC ROCK TYPES SEE ABBREVIATIONS)

Arithmetical Average A b c — b: Number of Analyses; c: Standard Deviation (variance ratio in brackets)

GRAMS/TON

General overall average –

Specific: intrusive • GI•; extrusive ▼ WI▼

IGNEOUS ROCK TYPES

Deep Sea Sediments	Ocean (Transfer Percentage)	Meteoritic Sulfides C = sulfide phase of chondrites
Shales	Metamorphic Rocks	Meteoritic Irons C = iron phase of chondrites
Sandstones	Other	Chondrites C = silicate phase of chondrites
Carbonates	Other	Universe including volatiles (Atoms per 10^6 Si Atoms)

Charge | Radius(Å) | Coordination

Radii listed as function of coordinations. Ionic radii based on 1.40 Å for O^{-2}

Volume (cubic Å)

Electrons in Each Quantum Group
QUANTUM GROUPS 1s thru 7s CORRESPOND TO SHELLS K thru Q; QUANTUM GROUPS FILLED BEFORE 1st GROUP LISTED AND EMPTY AFTER LAST GROUP LISTED (5g zero throughout)

Radius Ratio (cation ÷ ...) | Lattice Energy Coefficient | Ionization Potential (volts) | Miscellaneous Radii — Subscript keyed to list of abbreviations; ( )-Extrapolated value; [ ]-Calculated value

Naturally Occurring Isotopes

A# % Relative Abundance

Nuclear spin in multiples of h/2π indicated by superscript.

RADIOACTIVE ISOTOPE HALF-LIFE: d - Days; h - Hours; m - Minutes; s Seconds; y - Years

RADIATION DECAY: α-Alpha particle decay; β⁻ Negative beta decay; γ - Gamma ray (subsequent radiation)

Cost Range (reagent purity)

Common, independent, geochemically significant and/or host minerals with % element contained

Arithmetic average indicated where superscript indicates number of individual analyses and subscript indicates standard deviation. All other values calculated from idealized mineral formula

Atomic

Mn — 54.94 (91.20)

3d5 - 4s2

0	1.30	12	9.20					
+2	.80	6	2.14	.57	560	15.7		
+3	.66	6	1.20	.47	1300	32?		
+4	.57	4	.78	.41	2680	52?		
+4	.60	6	.90	.43				
+7	.44	4	.36	.31		~122		

$ 0.59-0.77/kg

ALABANDITE 63.0[1] RHODOCHROSITE 36.3[1]
PYROLUSITE 61.6 TRIPLITE 27.9
RHODONITE 41.9 FRANKLINITE 12.1

25 — 68.34 ▲ 58.23 ▲ -42.682 ▲ 41.49 ▲ 7.59 — 13.3

Fe — 55.85 (92.71)

3d6 - 4s2

0	1.24	8	7.99					
0	1.27	12	8.58					
+2	.74	6	1.70	.53	580	16.24		
+3	.64	6	1.10	.46	1280			

$ 1.33-1.73/kg

NATIVE ter. Fe. 95.1 PYRITE 44.1
HEMATITE 69.9 SIDERITE 35.0
MAGNETITE 63.3 JAROSITE 31.4
LAWRENCITE 44.1 GLAUCONITE ± 14

26 — 96.68 ▲ 85.76 ▲ -62.861 ▲ 43.11 ▲ 6.49 — 2.5

Co — 58.94 (97.84)

3d7 - 4s2

0	1.22	8	7.61					
0	1.26	12	8.38					
+2	.72	6	1.56	.51	620	17.3		
+3	.63	6	1.05	.45	1320			

$ 1.75-2.55/kg

COBALTOCALCITE 45.7 BIEBERITE 17.0
LINNAEITE 44.7 SKUTTERUDITE 11.3
COBALTITE 30.0 in PYRITE < 1.3
ERYTHRITE 23.9 in SPHALERITE 0.3m

27 — 105 ▲ 94 ▲ -68.9 ▲ 42.88 ▲ 6.8 — 37

Ni — 58.71 (97.46)

3d8 - 4s2

0	1.21	8	7.42					
0	1.24	12	7.99					
+2	.69	6	1.38	49	620	18.13		

$ 0.72-2.08/kg

ter. NICKEL-IRON 74.2 TREVORITE 23.3
MILLERITE 64.7 ANNABERGITE 20.7
NICCOLITE 42.0 GARNIERITE
PENTLANDITE 34.6 CHLOANTHITE 17.9

28 — 101.61 ▲ 90.77 ▲ -66.533 ▲ 43.59 ▲ 7.20 — 4.6

Br — 79.916 (132.66)

4p5

0	1.14	1	6.20					
-1	1.96	2	31.5					
+5	.45	4	.38	.32	55			
+7	.37	4	.21	.26		103.5		

$ 0.69-1.66/kg

BROMYRITE 31.0 in CARNALLITE 0.12
in LABRADORITE 20ppm in SYLVITE
EMBOLITE in PHOSGENITE ?
in HALLOYSITE 12ppm

35 — 7.34 ▲ 0.75 ▲ -0.551 ▲ 58.64 ▲ 36.4 — 6.6

Ru — 101.1 (167.8)

4d7-4f0-5s1

0	1.28	8	8.78					
0	1.32	12	9.63					
+4	.67	6	1.26	.48	2180			

$ 4.00-6.60/gm

LAURITE 61.1 in CHROMITE <.5 ppm
in SISERSKITE 11.1 in ILMENITE .004ppm
in AUROSMIRIDIUM 3.5

44 — 160 ▲ 149 ▲ -109.2 ▲ 44.57 ▲ 6.9 — 2.5

Rh — 102.91 (170.83)

4d8-4f0-5s1

0	1.30	8	9.20					
0	1.34	12	10.1					
+3	.68	6	1.32	.49	1250			

$ 5.00-8.00/gm

RHODITE in SPERRYLITE 1.7
in SISERSKITE 11.3 in PLATINUM 0.6
in PLATINIRIDIUM 6.9 in CHROMITE 0.5 ppm
in IRIDOSMINE 4.5 in ALLOPALLADIUM

45 — 138 ▲ 127 ▲ -93.09 ▲ 44.39 ▲ 7.6 — 150

Pd — 106.4 (176.6)

4d10

0	1.33	8	9.86					
0	1.37	12	10.8					
+2	.80	6	2.14	.57	640	19.8		
+4	.65	6	1.15	.46				

$ 2.50/gm

NATIVE Pd 100 BRAGGITE
STIBIOPALLADINITE PORPEZITE 10
In PLATINUM 37.1 ALLOPALLADIUM
POTARITE In MOLYBDENITE

46 — 93 ▲ 84 ▲ -61.6 ▲ 39.91 ▲ 8.9 — 8

Tc [99]* — (164.34)

4d6-4f0-5s1

0								
+7	.53	4	.62	.38				
+7	.56	6	.74	.40		95?		

probably does not occur in nature

43 — 9

I — 126.91 (210.67)

4f0-5s2-5p5

0	1.33	1	9.86					
0	1.35	2	10.3					
-1	2.20		44.6					
+5	.59	4	.86	.42	45			
+5	.62	6	1.00	.44				
+7	.48	4	.46	.34		90.2		

$ 1.16-2.34/gm

MARSHITE in BROMYRITE 15.1
LAUTARITE in MALACHITE
IODYRITE 54.1 in PHLOGOPITE
DIETZEITE 44.4 in VESUVIANITE

53 — 14.88 ▲ 4.63 ▲ -3.394 ▲ 62.28 ▲ 27.9 — 6.3

Pm [147]* — (244.02)

4f4-5s2-5p6-5d1-5f0-6s2

+3	1.02	6	4.44	.73	934			
+3	1.06	8	4.99	.76				

UNKNOWN IN NATURE ?

61

Er — 167.27 (278.67)

4f11-5s2-5p6-5d1-5f0-6s2

0	1.70	8	20.6					
0	1.76	12	22.8					
+3	.89	6	2.95	.64	999			

KEY

Element
S - SIDEROPHILE
C - CHALCOPHILE
A - ATMOPHILE
L - LITHOPHILE
B - BIOPHILE and LITHOPHILE

Atomic Weight
[#] Mass of isotope of longest half life; [*] - Mass of isotope of best known half life

(#) Weight of one atom x 10^{-24} grams

ABUNDANCES in ppm unless indicated otherwise

(FOR SPECIFIC ROCK TYPES SEE ABBREVIATIONS)

Arithmetical Average A — Number of Analyses b — Standard Deviation (variance ratio in brackets) c

General overall average –
Specific: intrusive ● GI ● ; extrusive ▼ WI ▼

IGNEOUS ROCK TYPES

GRAMS/TON

Deep Sea Sediments	Ocean (Transfer Percentage)	Meteoritic Sulfides C = sulfide phase of chondrites
Shales	Metamorphic Rocks	Meteoritic Irons C = iron phase of chondrites
Sandstones	Other	Chondrites C = silicate phase of chondrites
Carbonates	Other	Universe including volatiles (Atoms per 10^6 Si Atoms)

Charge

Radius (Å) — Radii listed as function of coordinations. Ionic radii based on 1.40 Å for O^{-2}

Coordination

Volume (cubic Å)

Electrons in Each Quantum Group
QUANTUM GROUPS Is thru 7s CORRESPOND TO SHELLS K thru Q; QUANTUM GROUPS FILLED BEFORE Ist GROUP LISTED AND EMPTY AFTER LAST GROUP LISTED (5g zero throughout)

Radius Ratio (cation / oxygen)

Lattice Energy Coefficient

Ionization Potential (volts)

Miscellaneous Radii — Subscript keyed to list of abbreviations; ( ) - Camouflaged value; [ ] - Calculated value

Naturally Occurring Isotopes

A# % Relative Abundance

Nuclear spin in multiples of h/2π indicated by superscript.

RADIOACTIVE ISOTOPE — RADIATION DECAY

HALF-LIFE
d - Days
h - Hours
m - Minutes
s Seconds
y - Years

α - Alpha particle decay
β - Negative beta decay
γ - Gamma ray (subsequent radiation)
e - Prominent internal conversion electron
IT - Isomeric transition

Cost Range (reagent purity)

Common, independent, geochemically significant and/or host minerals with % element contained

Arithmetic average indicated where superscript indicates number of individual analyses and subscript indicates standard deviation. All other values calculated from idealized mineral formula.

Atomic — STANDARD HEAT — STANDARD FREE — LOGARITHM OF — ENTROPY — ENTROPY

Atomic

39.944
(66.308)
0 | 1.91 | 29.2 | 3s2-3p6
$ 1.50-8.50/L
in GLAUCONITE in SYLVITE
in MUSCOVITE in ILLITE
in K FELDSPAR in LEUCITE
18 | 36.98 | 0.6

Kr
83.80
(139.1)
0 | 2.0 | 33.5 | 4p6
$ 25.00-30.00/L
36 | 39.19 | 28

Xe
131.30
(217.96)
0 | 2.2 | 44.6 | 4f0-5s2-5p6
$ 30.00-55.00/I
54 | 40.53 | 35

POTENTIALS AT 25°C.

Reaction	e_0 volts
$Cr^{+3} + e_0^- \rightleftharpoons Cr^{+2}$	−0.41
$Ti^{+3} + e_0^- \rightleftharpoons Ti^{+2}$	−0.37 ± 0.01
$V^{+3} + e_0^- \rightleftharpoons V^{+2}$	−0.20
$Sn^{+4} + 2e_0^- \rightleftharpoons Sn^{+2}$	0.154 ± 0.001
$Cu^{+2} + e_0^- \rightleftharpoons Cu^{+1}$	0.167 ± 0.001
$I_3^{-1} + 2e_0^- \rightleftharpoons 3I^{-1}$	0.535
$Fe^{+3} + e_0^- \rightleftharpoons Fe^{+2}$	0.771 ± 0.000[5]
$2Hg^{+2} + 2e_0^- \rightleftharpoons Hg_2^{+2}$	0.905 ± 0.001
$Tl^{+3} + 2e_0^- \rightleftharpoons Tl^{+1}$	1.25
$Mn^{+3} + e_0^- \rightleftharpoons Mn^{+2}$	1.51
$Ce^{+4} + e_0^- \rightleftharpoons Ce^{+3}$	1.610 ± 0.001
$H_2O_2 + 2H^{+1} + 2e_0^- \rightleftharpoons 2H_2O$	1.77
$Co^{+3} + e_0^- \rightleftharpoons Co^{+2}$	1.842 ± 0.001

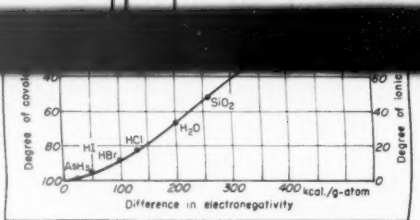
ELECTROCHEMICAL EQUIVALENTS

(Milligrams per Coulomb)

H^{+1}	0.010446	Po^{+6}	0.36269
D_2^{+1}	0.020878	Cl^{-1}	0.36743
N^{+5}	0.029032	Ta^{+5}	0.37488
C^{+4}	0.031113	In^{+3}	0.39641
B^{+3}	0.03737	K^{+1}	0.40514
He^{+0}	0.04147	U^{+6}	0.41117
Be^{+2}	0.04674	A^{+0}	0.41393
N^{+3}	0.048387	Sb^{+3}	0.42059
S^{+6}	0.05537	Bi^{+5}	0.43316
C^{+2}	0.06223	Sr^{+2}	0.45404
P^{+5}	0.06421	Hf^{+4}	0.46269
Li^{+1}	0.07192	La^{+3}	0.47986
Si^{+4}	0.07269	Ce^{+3}	0.48404
O^{-2}	0.082902	Pr^{+3}	0.48677
S^{+4}	0.08306	Os^{+4}	0.49611
Cr^{+6}	0.08983	Nd^{+3}	0.49834
Al^{+3}	0.09316	Ir^{+4}	0.50026
V^{+5}	0.10560	Pm^{+3}	0.50432
Ti^{+4}	0.12409	Pt^{+4}	0.50578
Mg^{+2}	0.12601	Sm^{+3}	0.51962
Se^{+6}	0.13637	Eu^{+3}	0.52504
Mn^{+4}	0.14230	Pb^{+4}	0.53681
Tc^{+7}	0.14478	Gd^{+3}	0.54179
As^{+5}	0.15254	Tb^{+3}	0.54991
Sc^{+3}	0.15579	Dy^{+3}	0.56069
Mo^{+6}	0.16580	Ho^{+3}	0.56974
S^{-2}	0.16611	Er^{+3}	0.57907
Cr^{+3}	0.17965	Cd^{+2}	0.58244
Ge^{+4}	0.18808	Tm^{+3}	0.58515
Nb^{+5}	0.19256	Yb^{+3}	0.59772
Fe^{+3}	0.19291	Pa^{+5}	0.59845
F^{-1}	0.19689	Th^{+4}	0.60135
Ca^{+2}	0.20767	Lu^{+3}	0.60446
Ne^{+0}	0.20915	Sn^{+2}	0.61503
Te^{+6}	0.22040	Cu^{+1}	0.65876
Zr^{+4}	0.23632	Au^{+3}	0.68117
Na^{+1}	0.23831	Tl^{+3}	0.70601
Ga^{+3}	0.24083	Ba^{+2}	0.71171
Sb^{+5}	0.25235	Bi^{+3}	0.72193
As^{+3}	0.25876	Ac^{+3}	0.78411
Ru^{+4}	0.26347	Br^{+1}	0.82815
Rh^{+4}	0.26661	Kr^{+0}	0.86736
Re^{+7}	0.27581	Rb^{+1}	0.88580
Pd^{+4}	0.27642	Hg^{+2}	1.03943
Mn^{+2}	0.28461	Pb^{+2}	1.07363
Fe^{+2}	0.28938	Ag^{+1}	1.11793
Ni^{+2}	0.30409	Ra^{+2}	1.17124
Co^{+2}	0.30539	I^{-1}	1.31523
Y^{+3}	0.30715	Xe^{+0}	1.36062
Sn^{+4}	0.30751	Cs^{+1}	1.37731
W^{+6}	0.31779	Au^{+1}	2.04352
Cu^{+2}	0.32938	Hg^{+1}	2.07886
Zn^{+2}	0.33876	Rn^{+0}	2.30052

SEQUENCE OF CATIONS ACCORDING TO FIELD STRENGTH

ELEMENT	COORD NO.	FIELD STRENGTH	ELEMENT	COORD NO.	FIELD STRENGTH
K^{+1}	8	0.13	Zr^{+4}	8	0.77
Na^{+1}	6	0.19	Be^{+2}	4	0.86
Li^{+1}	6	0.23	Fe^{+3}	6	0.76
Ba^{+2}	8	0.245		4	0.85



INDEX OF IONIC REPLACEMENT

atomic number $\times b A^{c}$ charge

$_{55}Cs^{+1}$	.02	$_{30}Zn^{+2}$	.14	$_{27}Co^{+3}$	.22
$_{37}Rb^{+1}$	.03	$_{26}Fe^{+2}$	.14	$_{31}Ga^{+3}$	.22
$_{81}Tl^{+1}$	.03	$_{29}Cu^{+2}$	.14	$_{13}Al^{+3}$ (6 FOLD COORD.)	.23
$_{19}K^{+1}$	03	$_{27}Co^{+2}$	.14	$_{4}Be^{+2}$	.24
$_{47}Ag^{+1}$	.04	$_{50}Sn^{+2}$	.14	$_{72}Hf^{+4}$	.27
$_{11}Na^{+1}$	.06	$_{28}Ni^{+2}$	.14	$_{41}Nb^{+4}$	.28
$_{29}Cu^{+1}$	.06	$_{12}Mg^{+2}$	.14	$_{74}W^{+4}$	.28
$_{56}Ba^{+2}$	.07	$_{90}Th^{+4}$	.16	$_{42}Mo^{+4}$	.28
$_{82}Pb^{+2}$	.08	$_{92}U^{+4}$	.19	$_{22}Ti^{+4}$	.28
$_{38}Sr^{+2}$	.08	$_{40}Zr^{+4}$	.20	$_{13}Al^{+3}$ (4 FOLD COORD.)	.35
$_{20}Ca^{+2}$	.09	$_{21}Sc^{+3}$	.20	$_{83}Bi^{+5}$	.35
$_{48}Cd^{+2}$	.09	$_{49}In^{+3}$	.20	$_{5}^{+3}$	.39
$_{3}I^{+1}$	.10	$_{23}V^{+3}$	.21	$_{32}Ge^{+4}$	.46
$_{57}La^{+3}$	.12	$_{25}Mn^{+3}$	.21	$_{14}Si^{+4}$	.48
$_{25}Mn^{+2}$	.13	$_{26}Fe^{+3}$	.22	$_{33}As^{+5}$	.60
$_{39}Y^{+3}$	.14	$_{24}Cr^{+3}$	.22	$_{15}P^{+5}$	.62

ENTROPIES S_0 OF IONS IN AQUEOUS SOLUTION AT 25°C.

(In cal. degree^{-1}.mol^{-1})
with reference to $S_{0,H^{+1}} = 0$

MnO_4^{-1}	46.7 ± 0.4	Sn^{+2}	−4.9 ± 1.0
Cs^{+1}	31.8 ± 0.6	Sr^{+2}	−7.3 ± 1.5
Mg^{+2}	31.6 ± 3	Ca^{+2}	−12.7 ± 0.6
Tl^{+1}	30.5 ± 0.4	CO_3^{-2}	−13.0 ± 1.0
NO_3^{-1}	29.9 ± 1	Cd^{+2}	−16.4 ± 1.5
Rb^{+1}	28.7 ± 0.7	Mn^{+2}	−19.1
IO_3^{-1}	28.0 ± 1.0	Zn^{+2}	−25.7 ± 1.0
NH_4^{+1}	26.6 ± 0.6	Fe^{+2}	−25.9 ± 1.0
I^{-1}	25.3	Cu^{+2}	−26 5 ± 1.0
CN^{-1}	25 ±5	Be^{+2}	−27
K^{+1}	24.2 ± 0.2	Co^{+2}	−27
HCO_3^{-1}	22.2 ± 0.8	Ni^{+2}	−31
$H_2PO_4^{-1}$	21.6 ± 0.3	Y^{+3}	−34
Br^{-1}	19.7	Tl^{+3}	−35
Hg_2^{+2}	19.7 ± 3	In^{+3}	−42
Ag^{+1}	17 54± 0.15	Sb^{+3}	−43
HS^{-1}	14.9 ± 1.0	Se^{+3}	−48
No^{+1}	14.0 ± 0.4	PO_4^{-3}	−52 ± 2
Cl^{-1}	13.50	Mn^{+3}	−59
CrO_4^{-2}	10.6 ± 1.0	As^{+3}	−60
$C_2O_4^{-2}$	9.6 ± 1.0	Rh^{+3}	−60
HPO_4^{-2}	8.7 ± 1.0	Fe^{+3}	−61 ± 5
Li^{+1}	4.7 ± 1.0	V^{+3}	−65
SO_4^{-2}	4.4 ± 0.5	Th^{+4}	−65
Pb^{+2}	3.9 ± 0.9	Cr^{+3}	−65
SO_3^{-2}	3 ± 3	U^{+4}	−67.9
OH^{-1}	2.49± 0.06	Ga^{+3}	−69
F^{-1}	2.3 ± 2	Al^{+3}	−76 ±10
Ba^{+2}	2.3 ± 0.3	Te^{+4}	−79
H	0.00	Zr^{+4}	−81
		Pb^{+4}	−84
		Sn^{+4}	−95
		Nb^{+4}	−101
		W^{+4}	−103
		Mo^{+4}	−103
		Os^{+4}	−104
		Ir^{+4}	−106
		Ru^{+4}	−108
		Ti^{+4}	−109
		V^{+4}	−114
		Ge^{+4}	−157
		Si^{+4}	−177

SOLUBILITY OF SULFIDES

Hg
Ag
Cu
Bi
Cd
Pb
Zn
Ni
Co
Fe^{+2}
Mn

upper replaces lower

ZONING

Hg (232)
Sb Cd (163)
Pb (156)
Zn (142)
Au, Te: Cu (143), As, Bi
Se, Ag
Sn (130)

EXCHANGEABILITY

In clay minerals

Li^{+1}
Na^{+1}
NH_4^{+1}
K^{+1}
Mg^{+2}
Rb^{+1}
NH_4^{+1}

AFFINITY FOR SULFUR IN MELT

Mn
Cu
Ni
Co

élément
Element
elemento
элемент

poids atomique
Atomgewicht
peso atómico
атомный вес

le poids d'un atome × 10^{-24} grammes
Gewicht eines Atoms × 10^{-24} Gramm
el peso de un átomo × 10^{-24} gramos
вес одного атома × 10^{-24} граммов

abondances
Gehalte
abundancias
относительное содержание

gramme/tonne
Gramm/Tonne
gramos/tonelada
содержание в граммах на тонну

moyenne
arithmétique
Arithmetischer
Durchschnitt
promedio aritmético
среднее
арифметическое

A

b numéro de analyses
Anzahl der Analysen
número de analisis
количество анализов

c déviation normale
Normale Streuung
deviación normal
нормальное отклонение

▲ extrusif
extrusiv
extrusivo
эффузивные породы

● intrusif
intrusiv
intrusivo
интрузивные породы

types de roches ignées
Eruptivgesteinsarten
tipos de roca ignea
типы магматических пород

hydrolysate pélagique Meerhydrolysat hidrolizato pelágico глубоководные осадки	océan Ozean océano океан	sulfite météoritique Meteorsulfid sulfito meteorítico метеорный сульфид
argile schisteuse Schieferton lutita глинистый сланец	roches métamorphiques Metamorphes Gestein rocas metamórficas метаморфические породы	fer météoritique Meteoreisen hierro meteorítico метеорное железо
grès Sandstein arenisca песчаник	autre Andere otro другие	silicate météoritique Meteorsilikat silicato meteorítico метеорный силикат
carbonate Karbonat carbonato карбонат	autre Andere otro другие	univers Universum universo вселенная

charge
Ladung
carga
заряд

rayon (Å)
Radius (Å)
radio
радиус /Å/

coordination
Koordination
coordinación
координационное
число

volume
Volumen
volúmen
объем

électrons dans chaque groupe quantum
Elektronen in jeder Quantumgruppe
electrones en cada grupo cuántico
число электронов в каждой квантовой группе

rapport des rayons
Radius Verhältnis
relación de los radios
соотношение радиусов

coefficient d'énergie en treillis
Gitterenergie-Koeffizient
coeficiente de la energía de celosía
коэффициент энергии
кристаллической решетки

potentiel d'ionisation (volts)
Ionisierungspotential (Volt)
potencial de ionización (voltios)
ионизационный потенциал
/в вольтах/

rayons divers
Verschiedene Radien
radios diversos
различные радиусы

isotopes occurrent naturellement
Natürliche Isotope
isotopos que ocurren de una manera natural
изотопы, встречающиеся в природе

pour cent d'abondance relative
% relativer Gehalt
% de abundancia relativo
% относительного содержания

ressort nucléaire indiqué par suscript
Kernspin angedeutet durch Strich über
dem betreffenden Zeichen
resorte nuclear indicado por superescrito
ядерный спин показан надстрочным
индексом

isotope radio-actif
Radioaktive Isotope
isotopo radioactivo
радиоактивный изотоп

décomposition de radiation
Strahlungszersetzung
descomposición por radiación
радиоактивный распад

demi-vie
Halbwert
media vida
полураспад

gamme de frais (pureté de réactif)
Kostbereich (Reagenz-Reinheit)
límites de gastos (pureza del reactivo)
пределы стоимости /чистота реагента/

minéraux avec pour cent du élément contenu
% Gehalt des Elements im Mineral
minerales con porcentaje del elemento contenido
% содержания элемента в минерале

numéro atomique
Atomzahl
número atómico
атомное число

chaleur de combination normale
Normale Bildungswärme
calor de formación normal
стандартная теплота
образования

énergie libre de formation normale
Normale freie Bildungsenergie
energía libre de formación normal
стандартная свободная
энергия образования

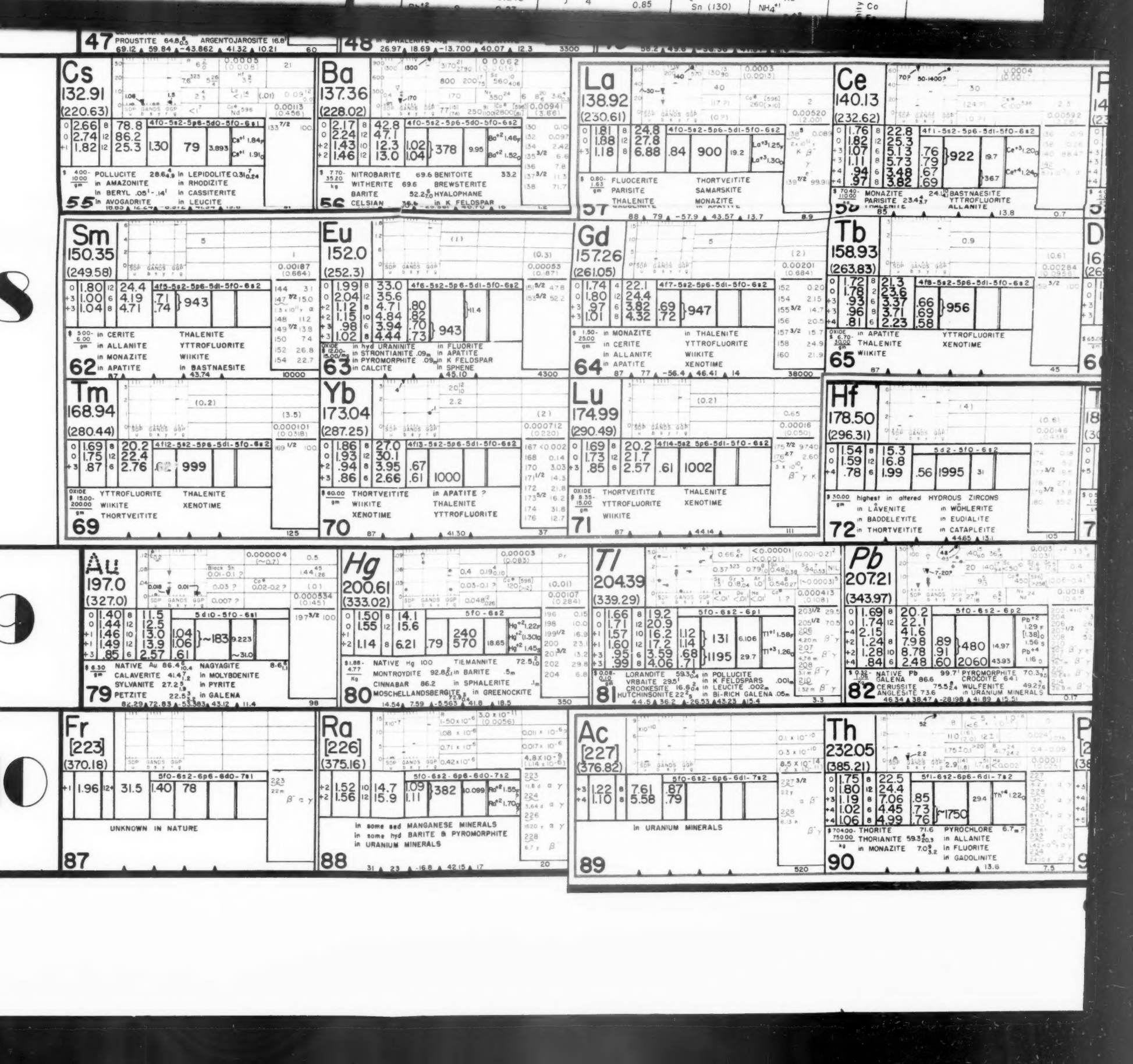
logarithme de la constante d'équilibre de formation
Logarithmus der Bildungsgleichgewichtskonstante
logarito de la constante de equilibrio de formación
логарифм постоянной равновесия образования

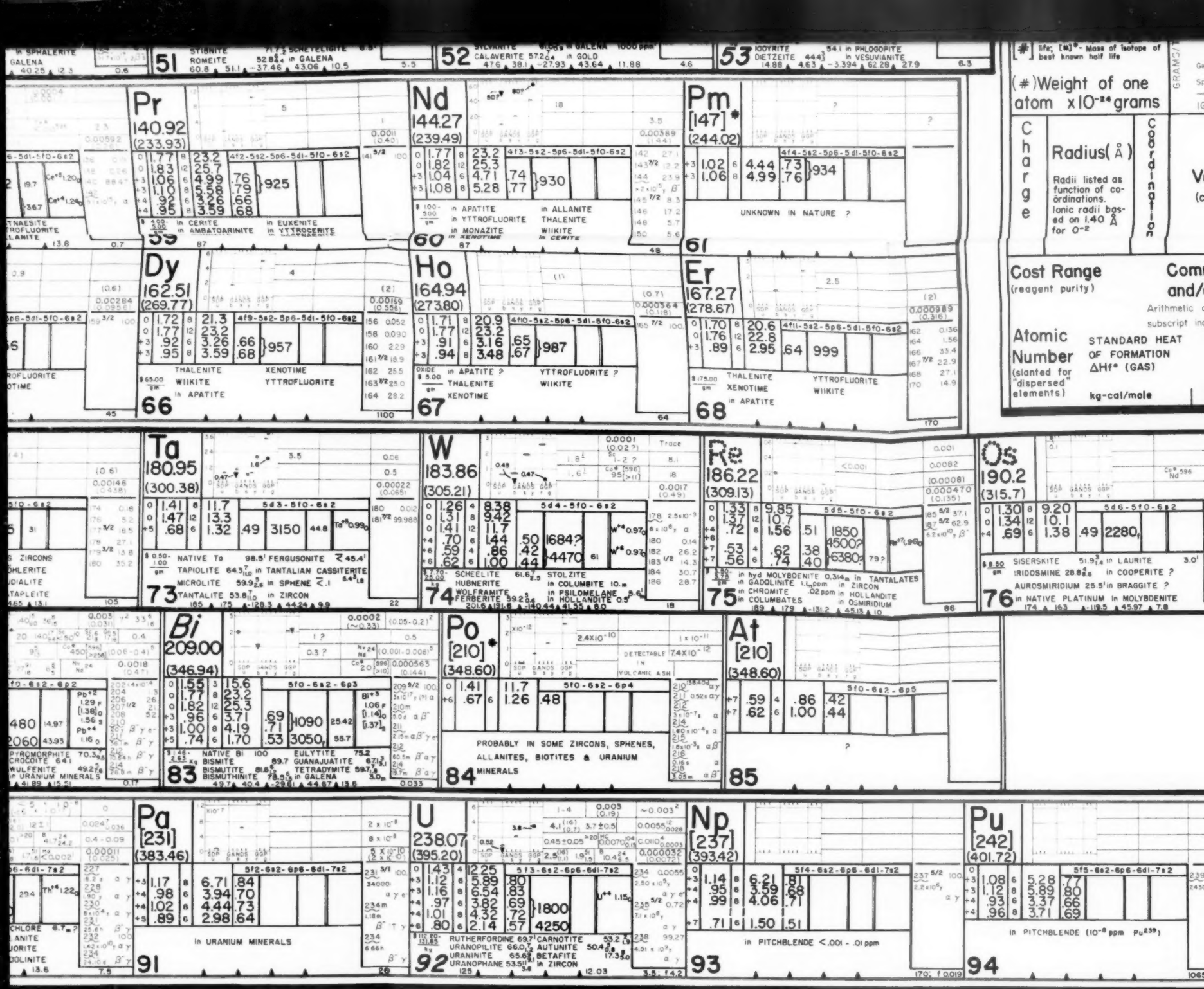
entropie à 25 degrés C. (gaz)
Entropie auf 25 Grad C. (Gas)
entropía a 25 grados C. (gas)
энтропия при 25° C.
/для газообразных тел/

entropie à 25 degrés C. (solide)
Entropie auf 25 Grad C. (fest)
entropía a 25 grados C. (solido)
энтропия при 25° C.
/для твердых тел/

la section transversale thermale de la capture de neutrons
Querschnitt durch thermischen Neutroneneinfang
sección transversal térmica de la captación de neutrones
эффективное сечение захвата тепловых нейтронов

Tous les data relatifs à l'abondance sont en grammes per tonne métrique sauf quand on indique le contraire.
Alle Gehaltsangaben, wo nicht anders angegeben, in Gramm per Tonne.
Todos los datos relativos a la abundancia se indican en gramos por tonelada métrica menos cuando se indica al contrario.
Все данные об относительном содержании, за исключением отдельно указанных случаев, приведены в граммах на тонну.


47
PROUSTITE 64.8
ARGENTOJAROSITE 16.8
69.12 ▲ 59.84 ▲ -43.862 ▲ 41.32 ▲ 10.21
60
48
26.97 ▲ 18.69 ▲ -13.700 ▲ 40.07 ▲ 12.3
3300
Cs
132.91
(220.63)
4f0-5s2-5p6-5d0-5f0-6s1
POLLUCITE 28.6
in AMAZONITE
in BERYL .05 .14
in AVOGADRITE
in LEPIDOLITE 0.3
in RHODIZITE
in CASSITERITE
in LEUCITE
55
Ba
137.36
(228.02)
4f0-5s2-5p6-5d0-5f0-6s2
NITROBARITE 69.6
WITHERITE 69.6
BARITE 52.2
CELSIAN 39.6
BENITOITE 33.2
BREWSTERITE
HYALOPHANE
in K FELDSPAR
56
La
138.92
(230.61)
4f0-5s2-5p6-5d1-5f0-6s2
FLUOCERITE
PARISITE
THALENITE
THORTVEITITE
SAMARSKITE
MONAZITE
57
88 ▲ 79 ▲ -57.9 ▲ 43.57 ▲ 13.7
8.9
Ce
140.13
(232.62)
4f1-5s2-5p6-5d1-6s2
MONAZITE 24.1
PARISITE 23.4
BASTNAESITE
YTTROFLUORITE
ALLANITE
58
85 ▲ 13.8
0.7
Sm
150.35
(249.58)
4f5-5s2-5p6-5d1-5f0-6s2
in CERITE
in ALLANITE
in MONAZITE
in APATITE
THALENITE
YTTROFLUORITE
WIIKITE
in BASTNAESITE
62
87 ▲ 45.74
10000
Eu
152.0
(252.3)
4f6-5s2-5p6-5d1-5f0-6s2
in hyd URANINITE
in STRONTIANITE .09
in PYROMORPHITE .09
in CALCITE
in FLUORITE
in APATITE
in K FELDSPAR
in SPHENE
63
4300
Gd
157.26
(261.05)
4f7-5s2-5p6-5d1-5f0-6s2
in MONAZITE
in CERITE
in ALLANITE
in APATITE
THALENITE
YTTROFLUORITE
WIIKITE
XENOTIME
64
87 ▲ 77 ▲ -56.4 ▲ 46.41 ▲ 14
38000
Tb
158.93
(263.83)
4f8-5s2-5p6-5d1-5f0-6s2
in APATITE
THALENITE
WIIKITE
YTTROFLUORITE
XENOTIME
65
87 ▲
45
Tm
168.94
(280.44)
4f12-5s2-5p6-5d1-5f0-6s2
YTTROFLUORITE
WIIKITE
THORTVEITITE
THALENITE
XENOTIME
69
125
Yb
173.04
(287.25)
4f13-5s2-5p6-5d1-5f0-6s2
THORTVEITITE
WIIKITE
XENOTIME
in APATITE ?
THALENITE
YTTROFLUORITE
70
87 ▲ 41.30 ▲
37
Lu
174.99
(290.49)
4f14-5s2 5p6-5d1-5f0-6s2
THORTVEITITE
YTTROFLUORITE
WIIKITE
THALENITE
XENOTIME
71
87 ▲ 44.14 ▲
111
Hf
178.50
(296.31)
5d2-5f0-6s2
highest in altered HYDROUS ZIRCONS
in LÄVENITE
in BADDELEYITE
in THORTVEITITE
in WÖHLERITE
in EUDIALITE
in CATAPLEITE
72
44.65 ▲ 13.1
105
Au
197.0
(327.0)
5d10-5f0-6s1
NATIVE Au 86.4
CALAVERITE 41.4
SYLVANITE 27.2
PETZITE 22.5
in MOLYBDENITE
in PYRITE
in GALENA
79
84.29 ▲ 72.63 ▲ -53.383 ▲ 43.12 ▲ 11.4
98
Hg
200.61
(333.02)
5f0-6s2
NATIVE Hg 100
MONTROYDITE 92.8
CINNABAR 86.2
MOSCHELLANDSBERGITE
TIEMANNITE 72.5
in BARITE .5
in SPHALERITE .1
in GREENOCKITE
80
14.54 ▲ 7.59 ▲ -5.563 ▲ 41.8 ▲ 18.5
350
Tl
204.39
(339.29)
5f0-6s2-6p1
LORANDITE 59.3
VRBAITE 29.5
CROOKESITE 16.6
HUTCHINSONITE 22.2
in POLLUCITE
in K FELDSPARS .001
in LEUCITE .002
in Bi-RICH GALENA .05
81
44.5 ▲ 36.2 ▲ -26.53 ▲ 45.25 ▲ 15.4
3.3
Pb
207.21
(343.97)
5f0-6s2-6p2
NATIVE Pb 99.7
GALENA 86.6
CERUSSITE 75.5
ANGLESITE 73.6
PYROMORPHITE 70.3
CROCOITE 64.1
WULFENITE 49.2
in URANIUM MINERALS
82
46.34 ▲ 38.47 ▲ -28.198 ▲ 41.89 ▲ 15.51
0.17
Fr
[223]
(370.18)
5f0-6s2-6p6-6d0-7s1
UNKNOWN IN NATURE
87
Ra
[226]
(375.16)
5f0-6s2-6p6-6d0-7s2
in some sed MANGANESE MINERALS
in some hyd BARITE & PYROMORPHITE
in URANIUM MINERALS
88
31 ▲ 23 ▲ -16.8 ▲ 42.15 ▲ 17
20
Ac
[227]
(376.82)
5f0-6s2-6p6-6d1-7s2
in URANIUM MINERALS
89
520
Th
232.05
(385.21)
5f1-6s2-6p6-6d1-7s2
THORITE 71.6
THORIANITE 59.3
in MONAZITE 7.0
PYROCHLORE 6.7 ?
in ALLANITE
in FLUORITE
in GADOLINITE
90
13.6
7.5



GEOCHEMICAL TABLE OF THE ELEMENTS FOR 1959

of isotope of life

of one ⁴grams

(Å)

Coordination

Volume (cubic Å)

GRAMSJ

C = Standard Deviation (variance ratio in brackets)
General overall average –
Specific { intrusive ● GI ●
extrusive ▼ WI ▼
IGNEOUS ROCK TYPES

Sandstones | Other
Carbonates | Other

Chondrites
C = silicate phase of chondrites

Universe including volatiles (Atoms per 10^6 Si Atoms)

Naturally Occurring Isotopes
A* % Relative Abundance
Nuclear spin in multiples of h/2π indicated by superscript.

RADIOACTIVE ISOTOPE — RADIATION DECAY
HALF-LIFE
d - Days
h - Hours
m - Minutes
s Seconds
y - Years
γ - Gamma ray (subsequent radiation)
e⁻ - Prominent internal conversion electron
IT - Isomeric transition
K - K electron capture
L - L electron capture
α - Alpha particle decay
β⁻ - Negative beta decay

Thermal neutron absorption cross section in barns

Electrons in Each Quantum Group
QUANTUM GROUPS Is thru 7s CORRESPOND TO SHELLS K thru Q; QUANTUM GROUPS FILLED BEFORE 1st GROUP LISTED AND EMPTY AFTER LAST GROUP LISTED (5g zero throughout)

Radius Ratio (cation / anion)

Lattice Energy Coefficient

Ionization Potential (volts)

Miscellaneous Radii
Subscript keyed to list of abbreviations
( )-Extrapolated value
[ ]-Calculated value

Common, independent, geochemically significant and/or host minerals with % element contained

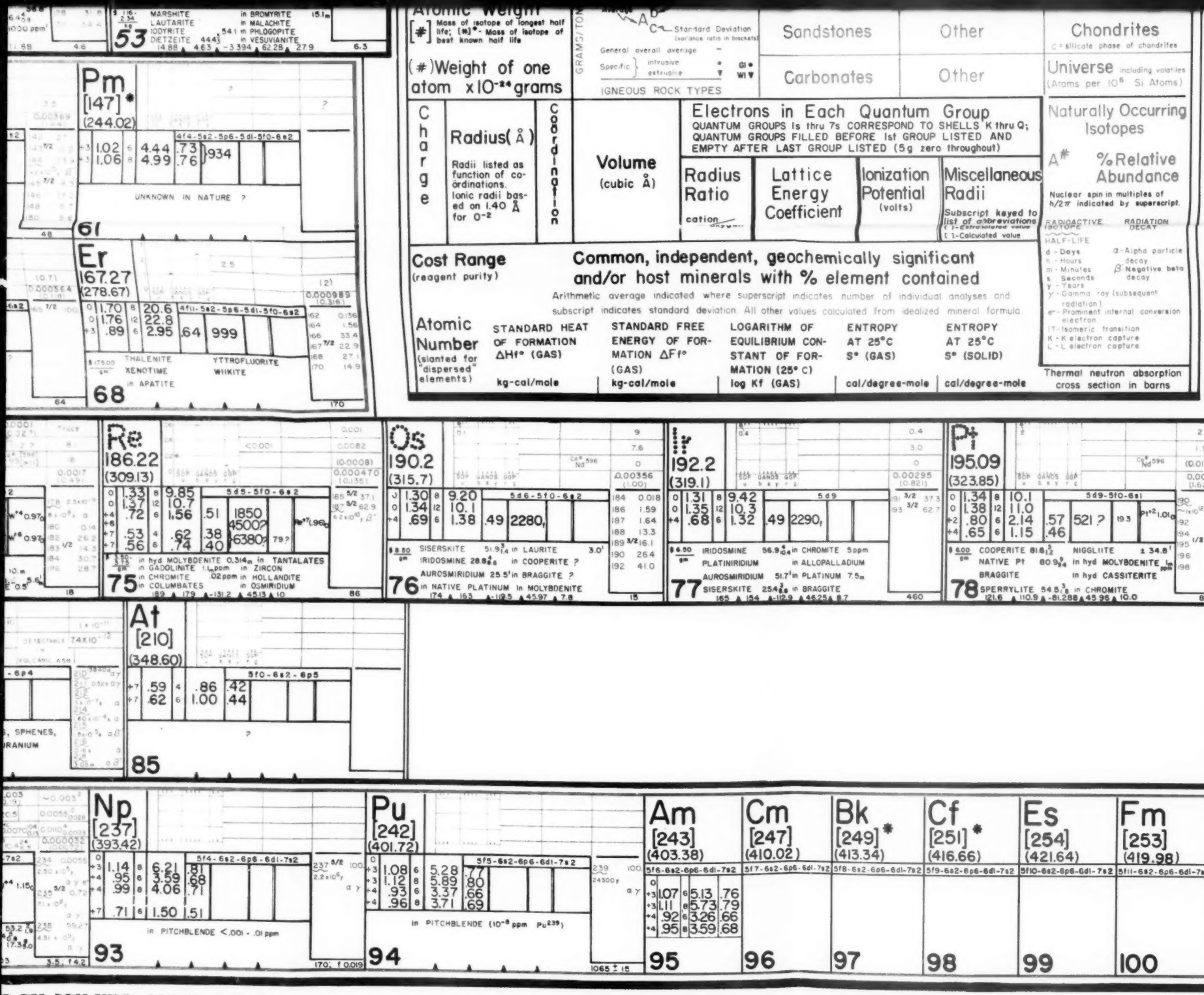
Arithmetic average indicated where superscript indicates number of individual analyses and subscript indicates standard deviation. All other values calculated from idealized mineral formula.

STANDARD HEAT OF FORMATION f° (GAS)	STANDARD FREE ENERGY OF FORMATION ΔFf° (GAS)	LOGARITHM OF EQUILIBRIUM CONSTANT OF FORMATION (25° C)	ENTROPY AT 25°C S° (GAS)	ENTROPY AT 25°C S° (SOLID)
cal/mole	kg-cal/mole	log Kf (GAS)	cal/degree-mole	cal/degree-mole

54

40.53

| | | |



LEMENTS FOR 1959

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absorption
in barns

54 40.53

	2	
	1.9	
Ca^{*}_{Nd} 596	(0.01)	
	0.0059	
	(1.625)	
190	0.012	
192	0.78	
194	32.8	
195 1/2	33.7	
196	25.4	
198	7.2	

-6s1
93 Pt^{+2} 1.01α
± 34.8¹
YBDENITE
SITERITE
TE
10.0
8

Rn
[222]
(368.52)
9.0×10^{-16} (0.2 5)
2.2×10^{-13}
in natural gas
10-520 micromicrocuries per liter
0 ± 2.4 ± 58 5f0-6s2-6p6
219 3.92s α γ
220 54.5s α
222 3.825d α
in URANIUM MINERALS
in some hyd BARITE & PYROMORPHITE
in some hyd MANGANESE MINERALS
86 42.10

Fm	Md	No	
[253]	[256]	[253]	
(419.98)	(424.96)	(419.98)	
5f11-6s2-6p6-6d1-7s2	5f12-6s2-6p6-6d1-7s2	5f13-6s2-6p6-6d1-7s2	5f14-6s2-6p6-6d1-7s2
100	101	102	103

Ru^{+4}	0.26347
Rh^{+4}	0 26661
Re^{+7}	0.27581
Pd^{+4}	0.27642
Mn^{+2}	0.28461
Fe^{+2}	0.28938
Ni^{+2}	0.30409
Co^{+2}	0.30539
Y^{+3}	0.30715
Sn^{+4}	0.30751
W^{+6}	0.31779
Cu^{+2}	0.32938
Zn^{+2}	0.33876
Br^{+1}	0.82613
Kr^{+0}	0.86736
Rb^{+1}	0.88580
Hg^{+2}	1.03943
Pb^{+2}	1.07363
Ag^{+1}	1.11793
Ra^{+2}	1.17124
I^{-1}	1.31523
Xe^{+0}	1.36062
Cs^{+1}	1.37731
Au^{+1}	2.04352
Hg^{+1}	2.07886
Rn^{+0}	2.30052

H 0.00

SOLUBILITY OF SULFIDES

Hg
Ag
Cu
Bi
Cd
Pb
Zn
Ni
Co
Fe^{+2}
Mn

upper replaces lower

Zr^{+4}	−81
Pb^{+4}	−84
Sn^{+4}	−95
Nb^{+4}	−101
W^{+4}	−103
Mo^{+4}	−103
Os^{+4}	−104
Ir^{+4}	−106
Ru^{+4}	−108
Ti^{+4}	−109
V^{+4}	−114
Ge^{+4}	−157
Si^{+4}	−177

SEQUENCE OF CATIONS ACCORDING TO FIELD STRENGTH

ELEMENT	COÖRD NO.	FIELD STRENGTH	ELEMENT	COÖRD NO.	FIELD STRENGTH
K^{+1}	8	0.13	Zr^{+4}	8	0.77
Na^{+1}	6	0.19	Be^{+2}	4	0.86
Li^{+1}	6	0.23	Fe^{+3}	6	0.76
Ba^{+2}	8	0.245		4	0.85
Pb^{+2}	8	0.27	Al^{+3}	6	0.84
Sr^{+2}	8	0.28		4	0.96
Ca^{+2}	9	0.33	Ti^{+4}	6	1.04
Mn^{+2}	6	0.40	B^{+3}	4	1.34
Fe^{+2}	6	0.43		3	1.63
Zn^{+2}	4	0.49	Si^{+4}	4	1.57
Mg^{+2}	6	0.45	P^{+5}	4	2.1
	4	0.53			

ZONING

Hg (232)
Sb Cd (163)
Pb (156)
Zn (142) } Se Ag
Cu (143)
Au, Te { As, Bi
Sn (130)
W Mo Ni (98)
Co (93) Mn (87)

HEATED SOURCE

Numbers in parentheses are stability factors Fe (94) and S present throughout series

EXCHANGEABILITY

In clay minerals

Li^{+1}
Na^{+1}
NH_4^{+1}
K^{+1}
Mg^{+2}
Rb^{+1}
NH_4^{+1}
Ca^{+2}
Sr^{+2}, Ba^{+2} } Co^{+3}
Al^{+3}

lower replaces upper

AFFINITY FOR SULFUR IN MELT

increasing affinity: Mn, Cu, Ni, Co, Fe, Sn, Zn, Pb, Sb, Ag

DISCONTINUOUS REACTION SERIES

Minerals — Vol. of unit cell — Na, K / Al — Si / Al

(−4.9) Olivine (Mg, Fe)
(−4.0) Ca-pyroxene, Mg-pyroxene, Alk-pyroxene
(−3.9) Amphibole
(−3.8) Biotite

0.0 ∞ 3.0 1.0

(Muscovite)
(−3.0) Quartz
Zeolites
Hydrothermal minerals

CONTINUOUS REACTION SERIES

Si / Al — Na, K / Al — Vol. of unit cell — Minerals

1.0 0.0 + (Anorthite)
Bytownite
Labradorite (−2.9)
Andesine
Oligoclase
K-feldspar
Albite

Numbers in parentheses are relative lattice energies.

HYDROXIDE PRECIPITATION pH'S

(From dilute solutions)

pH 12 11 10 9 8 7 6 5 4 3 2 1

Mg^{+2}
Mn^{+2}
La^{+3}
Ag^{+1}
Ce^{+3}
Hg^{+2} (chloride)
Pr^{+3}
Zr^{+2}, Nd^{+3}
Co^{+2}, Y^{+3}, Sm^{+3}
Ca^{+2}, Ni^{+2}
Pb^{+2}
Be^{+2}
Fe^{+3}
Cu^{+2}, Cr^{+3}
U^{+4}
Al^{+3}
Th^{+4}
In^{+3}
Hg^{+4}
Ce^{+4}
Fe^{+3}, Zr^{+4}, Sn^{+2}, Hg^{+2} (nitrate)

(ALKALI SOILS)
(SEA WATER)
(RAIN WATER)
(PEAT WATER)
(MINE WATER)
(ACID THERMAL SPRINGS)

ABBREVIATIONS

A - anorthosite
Ac - achondrite
An - anhydrite and/or gypsum
Ap - aplite
Ar - arkose
B - bauxite
Bm - blue mud
C - chondrite
Co - coal
Co* - coal ash
D - diorite - andesite
Di - diatom ooze
Do - dolomite
Du - dunite
F - ionic radius in fluorides
f - Fersman lattice energy coefficient
G - granite - rhyolite
Gb - gabbro - basalt
Gl - globigerina ooze
Gn - gneiss
Gr - granodiorite - dacite
gr - gray
Gy - graywacke
Gs - greisen
H - hydrated radius
Ha - halite and/or rock salt
HC - crude oil
HC* - crude oil ash
hex - hexagonal
Hf - hornfels
hyd - hydrothermal
Ls - limestone
La - laterite
M - marble
m - maximum
ma - marine
mag - magmatic
N - norite
Nd - not detected
nm - non-marine
Ns - nepheline syenite-phonolite
Nv - novaculite and/or chert
O - radius in oxides
Ob - obsidian
org - organic
P - peridotite - limbergite
Pg - pegmatite
Po - porphyry
Pr - present
Q - quartzite
R - red clay
rhb - rhombohedral
S - sulfide or radius in sulfides
Sc - schist
sed - sediment
Sh - shale
Sl - slate
Ss - sandstone
Sy - syenite - trachyte
T - tetrahedral radius
ter - terrestrial
Tr - trace
WT - welded tuff

Gl
Introd
Loc
Sea
Sco
Me
Pre
Ack
Struct
Des
Gen
Ana
Petrog
Gen
Roc
Miner
Min
Ten
Age
Zirc
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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 70, PP. 1185–1216, 10 FIGS., 5 PLS. SEPTEMBER 1959

GEOLOGIC EVOLUTION OF THE BEARTOOTH MOUNTAINS, MONTANA AND WYOMING

PART 3. GARDNER LAKE AREA, WYOMING

BY RAE L. HARRIS, JR.

ABSTRACT

The Gardner Lake area is one of the key areas being studied in detail in the Beartooth Mountains, Montana and Wyoming. Foliation, compositional banding, and rock units indicate open southward-plunging folds traceable through metasediments and migmatites into granitic gneisses. The attitude of axial-plane foliation in highly contorted metasediments is found also in foliation trends of the gneisses. Complete gradations from metasediments to pink leucocratic gneiss are indicated by distribution of mappable units, abundance and composition of feldspars and ferromagnesian minerals, percentage and character of rounded and overgrown zircons, length-width ratios of zircons, and variations in chemical analyses. Replacement *in situ* by hot alkaline solutions seems the most likely origin for the granitic gneisses. Boudinage and rotation of amphibolite blocks within highly contorted feldspathized strata denote regional metamorphism prior to granitization. Mafic intrusive bodies are pregranitization, penegrantization, and postgranitization in age, and their major trends, northwest and northeast, suggest that the present topographic expression is controlled by structural elements developed during feldspathization. Seven K-A and Rb-Sr ages on widely dispersed micas and feldspars indicate this event as 2.7 billion years ago.

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Introduction

Location and Regional Geology

The Beartooth Mountains, the Owl Creek and Bridger ranges to the south, and the Pryor and Bighorn blocks to the east outline the topographic and structural Bighorn Basin (Fig. 1). The basin contains more than 15,000 feet of Paleozoic, Mesozoic, and Cenozoic sediments (Bucher, Thom, and Chamberlin, 1934, p. 187). The axis of the Bighorn Basin trends northwest and passes under the overthrust eastern corner of the Beartooth block near Red Lodge, Montana (Chamberlin, 1940, p. 691). All basin strata thin abruptly upon crossing the Nye-Bowler lineament (Wilson, 1936, p. 1181; Chamberlin, 1940, p. 694), and remnants of Paleozoic sediments on the present mountain blocks are also thin in relation to the basin facies (Chamberlin, 1940, p. 674). These differences in thickness are evidence of repeated displacements between basin and mountain blocks since at least earliest Paleozoic times. The present topography resulted from uplift and thrusting during the Laramide Revolution.

Much of the southwestern border of the Beartooth block is covered by Tertiary volcanic rocks which form the Absaroka Mountains and those of Yellowstone Park. The Beartooth block can be subdivided into two asymmetrical units. The northern half, including the Snowy Mountains, is dominated by overthrusting toward the southwest, whereas south of the Stillwater River thrusting has been toward the northeast. The Precambrian erosional surface is tilted in both cases in the opposite direction (Bucher, Thom, and Chamberlin, 1934, p. 174; Wilson, 1936, p. 1181).

The core of the Beartooth Mountains consists mainly of granitic gneisses and amphibolites with minor migmatites and rare metasediments and associated mafic intrusive rocks. It is exposed for 60 miles, trending northwest, and is approximately 30 miles wide. To the east and west the core grades into a zone of migmatites and granitic gneisses with minor metasediments (E. C. H. Lammers, 1939, unpub. ms.). Along the northeast margin of the block, Paleozoic marine strata have been overturned by Laramide movements. Felsic porphyry intrusive rocks of Laramide age are emplaced peripherally to the central core.

The Gardner Lake area is located within the core of the Beartooth Mountains, approximately 4 miles from the eastern zone of granitic gneisses, migmatites, and metasediments. U. S. Highway 12 traverses the area, with Beartooth Pass at an elevation of 10,947 feet in the north-central portion of the mapped area. The principal geomorphic features result from alpine glaciation and are best described as biscuit-board topography (Fig. 2).

Beartooth Research Project

During a reconnaissance of the Beartooth Mountains in the summer of 1952, Prof. Arie Poldervaart recognized the unusual opportunities in the region for long-term group research on fundamental problems of Precambrian geology. A strip approximately 4 miles wide was tentatively blocked out across the Beartooth Mountains (Fig. 3). Location of this strip was facilitated by the excellent aerial photographs available and influenced by U. S. Highway 12 which traverses the region. The project was initiated in 1953 with mapping in the Quad Creek area (Eckelmann and Poldervaart, 1957), first of the key areas which make up the strip (Fig. 3). Emphasis has been on structures preserved within the granitic gneisses

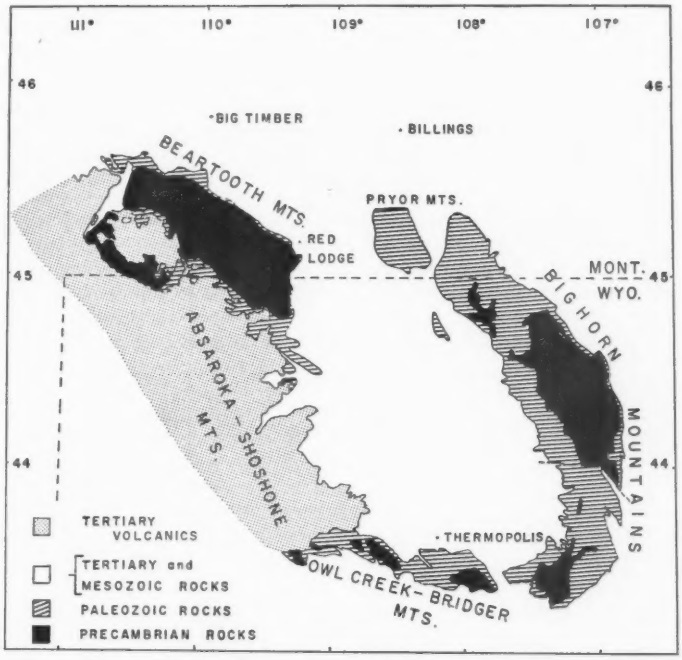


FIGURE 1.—INDEX MAP OF BIGHORN BASIN AND PERIPHERAL MOUNTAIN RANGES

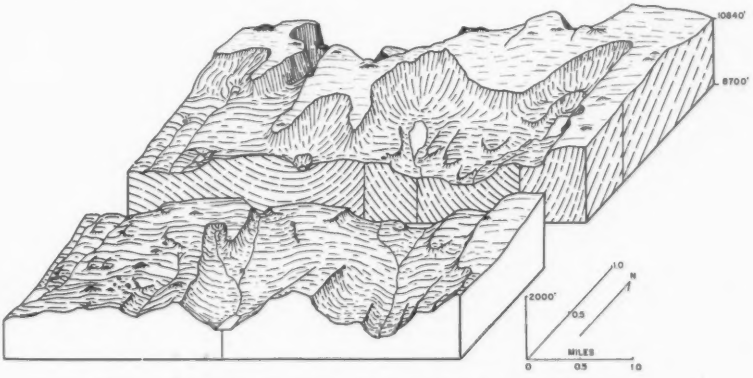


FIGURE 2.—BLOCK DIAGRAM, GARDNER LAKE AREA, WYOMING

petrogenesis, and geochronology. In addition to detailed mapping, regional studies of jointing (Spencer, 1959), dike swarms, and Archean metasediments have been included in the project.

Gardner Lake was chosen as a key area because of the large amount of exposure due to close proximity of six separate glacial cirques, ready access from the highway, and the excellent foliation and banding of the granitic rocks.

Scope

The emphasis in this study is on structures which existed in the metasediments prior to granitization. Investigation of these structures

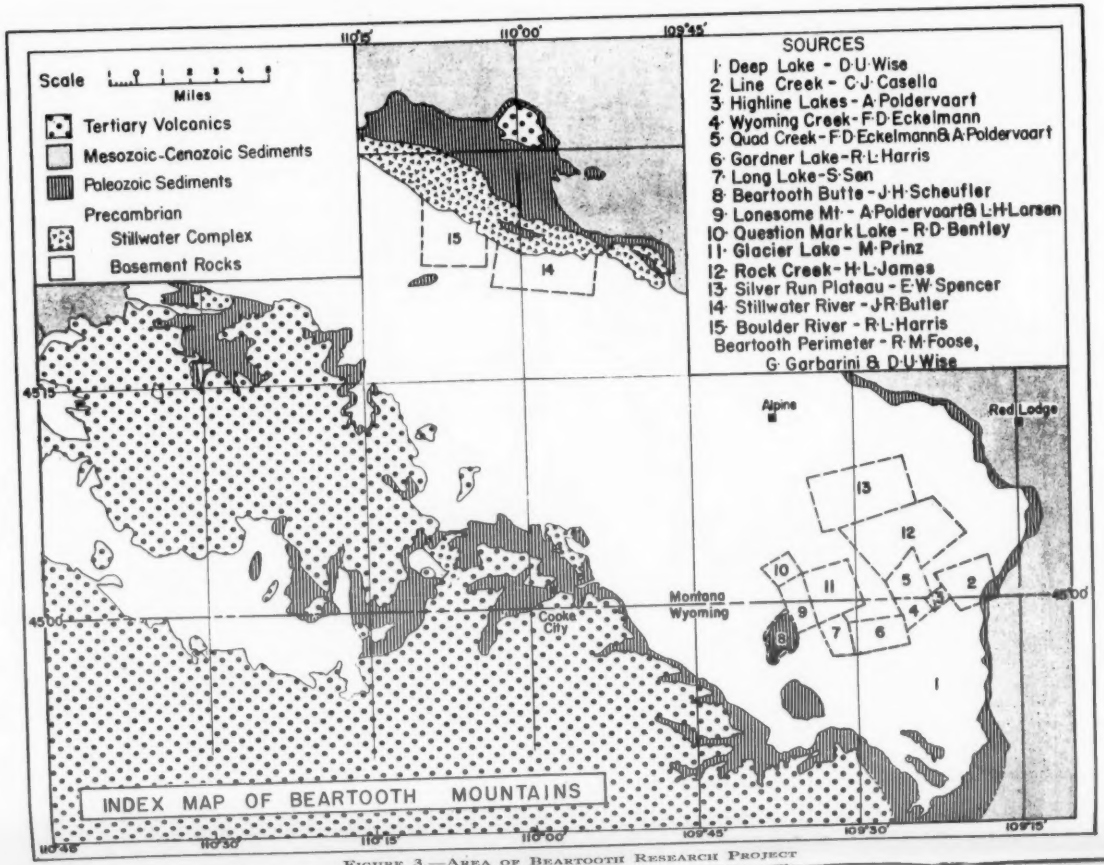


FIGURE 3.—AREA OF BEARTOOTH RESEARCH PROJECT

requires an explanation of the changes which the rocks have undergone, and this in turn leads logically to a general geochronology for the region. Much reliance has been placed upon field studies, since the investigation is primarily structural. Field observations and rock classifications have been checked by petrographic work and chemical analyses of rocks and minerals. However, the detailed petrology of the transformation process is not within the bounds of this paper. It is expected that a synthesis of chemical and mineralogical data accumulated in each area will appear as a separate paper dealing with the granitization process.

Laramide felsic porphyry dikes in the area are considered only as they relate to structure. Their petrography is not a part of the present investigation; for this the reader is referred to Rouse *et al.* (1937).

Methods of Investigation

Field work for this investigation was conducted during the summers of 1955 and 1956. All observation points were plotted directly on an enlargement of an aerial photograph furnished by the U. S. Geological Survey. The mapping scale was 1:6000 (500 feet equals 1 inch). Generally it was possible to locate stations on the photograph within 10 feet, but on grass-covered slopes an error of 200 feet would not be unexpected. The larger errors in location of stations are few, since outcrops are rarely associated with grassy slopes. All dips and strikes taken on foliation have been plotted on the final map, and no attempt was made in the field to select foliation planes based on impressions of true bedding versus apparent bedding due to flowage or other causes.

Outcrop patterns were sketched in the field wherever contrast in rock type permitted. The writer collected 315 samples, representative of all rock varieties and textures; each sample was accurately located on the field photograph. Final drafting of the map was by direct tracing of original field photographs, using the U. S. Geological Survey topographic map of the area as control for scale and elevation.

Standard laboratory procedures were used and involved the examination of thin sections of all samples collected. Mineral compositions of 30 specimens were obtained using a Chayes point counter; volume per cent was later converted to weight per cent. Three sections cut at right angles were used in the quantitative investigation of all foliated rocks. Specific gravity was determined both directly and by calculation from the modes. Indices of refraction were obtained using immersion methods, the fluids checked with a refractometer. All extinction angles and 2V values were obtained using a 4-axes universal stage. Zircon investigations involved heavy liquid, magnetic, and acid separations (Poldervaart, 1955, p. 435; Eckelmann and Kulp, 1956, p. 307; Larsen and Poldervaart, 1958, p. 550–553).

Previous Work

In the Cooke City mining district, Lovering (1929) found evidence which he interpreted to indicate two intrusive granites. E. C. H. Lammers (1939, unpub. ms.) demonstrated that structures formed during the Precambrian controlled the Laramide tectonics in the Beartooth block and described Lovering's two granites as textural and compositional variants of one magma contaminated by invaded rocks. These and other reconnaissance studies concluded that a granite magma had intruded the area by *lit-par-lit* injection, stoping, assimilation, and replacement; foliation in the granite was interpreted as platy flow structure.

More recent investigations in the area were carried out by Eckelmann and Poldervaart (1957), who described a plunging synclinal structure traceable in undoubted metasediments, migmatites, and granitic gneisses. The structure is accompanied by progressive changes in texture and composition of the lithologic units involved. D. U. Wise (1957, unpub. Ph.D. thesis, Princeton Univ.), concentrating on the structure of the Laramide uplift at the southeastern corner of the Beartooth block, reported open, southward-plunging folds throughout the granitic rocks in that area. Spencer (1957; 1959) completed a comprehensive investigation of fractures in the granitic core which indicated Precambrian control of all subsequent deformations (*cf.* Foose, Garbarini, and Wise, 1957).

Other workers who have contributed to various aspects of the geology of the Beartooth block include Bucher, Thom, and Chamberlin (1934), Cloos and Cloos (1934), Schafer (1937), Lane (1938), Rouse *et al.* (1937), James (1946), Stobbe (1952), and Thom (1955).

Acknowledgments

The facilities of the Yellowstone-Bighorn Research Association, Red Lodge, Montana, have been used during the periods of field work. This project is part of a program of research

FIGURE 3.—AREA OF BEARTOOTH RESEARCH PROJECT

in Archean rocks of the Beartooth Mountains, directed by Prof. Arie Poldervaart and integrated with investigations of other association members throughout the Bighorn Basin region.

The National Science Foundation (project NSF-G-1717), the Higgins Fund of Columbia University, and the Yellowstone-Bighorn Research Association financed the work.

Among those who have contributed substantially to this effort, the following deserve special recognition, and their aid is gratefully acknowledged: Charles H. Behre, Jr., Walter H. Bucher, F. Donald Eckelmann, Paul W. Gast, Heinrich D. Holland, Paul F. Kerr, Sidney Paige, J. Frank Schairer, Saurindranath Sen, and Edgar W. Spencer.

Structural Geology

Description of Mapped Structures

GENERAL STATEMENT: The geologic map (Pl. 5) has been drafted using lithologic units chosen for easy recognition in the field. High relief within the area and the large scale of the map produce outcrop patterns which tend to give a misleading impression. The principal structural features are the Blackstone Lake syncline, the syncline between Gardner Lake and Christmas Lake (hereafter referred to as the False Summit syncline), the Christmas Lake syncline, the pattern of mafic dikes, and the Laramide fault system with associated felsic porphyry dikes.

BLACKSTONE LAKE SYNCLINE: The Blackstone Lake syncline trends a little west of north and plunges south at approximately 45°. The minimum distance across the trough, east-west, is approximately 2 miles. The west limb of the fold appears to strike N 15° W., but this angle is due in part to local relief. The average slope of the topography is approximately 7° S.; if the limb is assumed to dip 50° E., calculation shows a deviation in strike of nearly 6° toward the west. An extreme case is shown in the northwest corner of the map, where apparent strike is deflected nearly 90° by a steep cliff.

The eastern limb is well exposed in the cirque wall above Gardner Lake, as is the trough in the cirque just north of Beartooth Pass (Pl. 1, fig. 1). In both places, the rock units dip approximately 90° to the slope; thus outcrop projections are unusually narrow. Along this limb, southwesterly dips abruptly cease just south of Gardner Lake, with a shift to the southeast. This abrupt change of 90° in strike is attributed to a Laramide high-angle fault.

FALSE SUMMIT SYNCLINE: The False Summit syncline trends slightly east of north and plunges south at approximately 40°. The trough has a minimum width of nearly 1½ miles and appears to be more closed than the Blackstone Lake syncline, although here too topography has caused a deflection in trend of the lithologic bands. Relief in this instance has caused an

---

PLATE 1.—CIRQUE WALL AND OUTCROP ILLUSTRATING STRATIFICATION IN THE GRANITIC GNEISSES AND EXAMPLES OF FLOWAGE IN HIGHLY CONTORTED BANDED MIGMATITE

FIGURE 1.—Headwall of Mirror Lake cirque looking east. A 500-foot section of stratified granitic gneisses illustrating the southerly dip and continuity of structure is shown.

FIGURE 2.—Minor southward-plunging anticlinal fold on west limb of the Blackstone Lake syncline.

FIGURE 3.—Extreme example of flowage in highly contorted banded migmatite of the Christmas Lake syncline. Plastic nature of deformation is indicated by random orientation of folds.

FIGURE 4.—Contrast in original composition producing boudinage structures in highly contorted banded migmatite.

PLATE 2.—MAFIC DIKES, DISCORDANT PEGMATITE, AND ISOCLINAL FLOW FOLDING

FIGURE 1.—Bowl-shaped metanorite dike occupying an arcuate joint in foliated granitic gneiss just north of Long Lake.

FIGURE 2.—Nearly vertical unmetamorphosed Precambrian quartz dolerite dike trending northwest. Dike passes through Christmas Lake and is more than 100 feet thick. Photograph taken looking northwest.

FIGURE 3.—Light-colored discordant pegmatite surrounding blocks in massive amphibolite. Isolated lenses have developed popcorn texture by plagioclase growth.

FIGURE 4.—Isoclinal flow folding preserved in granitic gneiss. The foliation is parallel to the axial plane of the major folds in the area.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

CIRQUE WALL AND OUTCROP ILLUSTRATING STRATIFICATION IN THE GRANITIC GNEISSES AND EXAMPLES OF FLOWAGE IN HIGHLY CONTORTED BANDED MIGMATITE

FIGURE 1

FIGURE 2

FIGURE 3

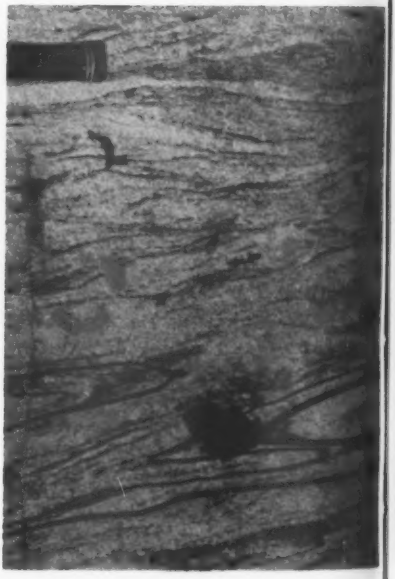


FIGURE 4

MAFIC DIKES, DISCORDANT PEGMATITE, AND ISOCLINAL FLOW FOLDING

FIGURE 1

FIGURE 2

FIGURE 3

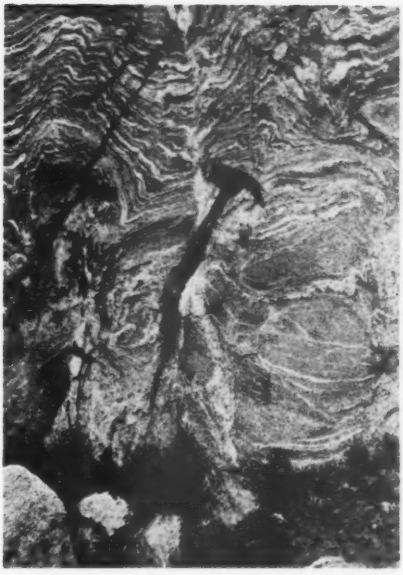
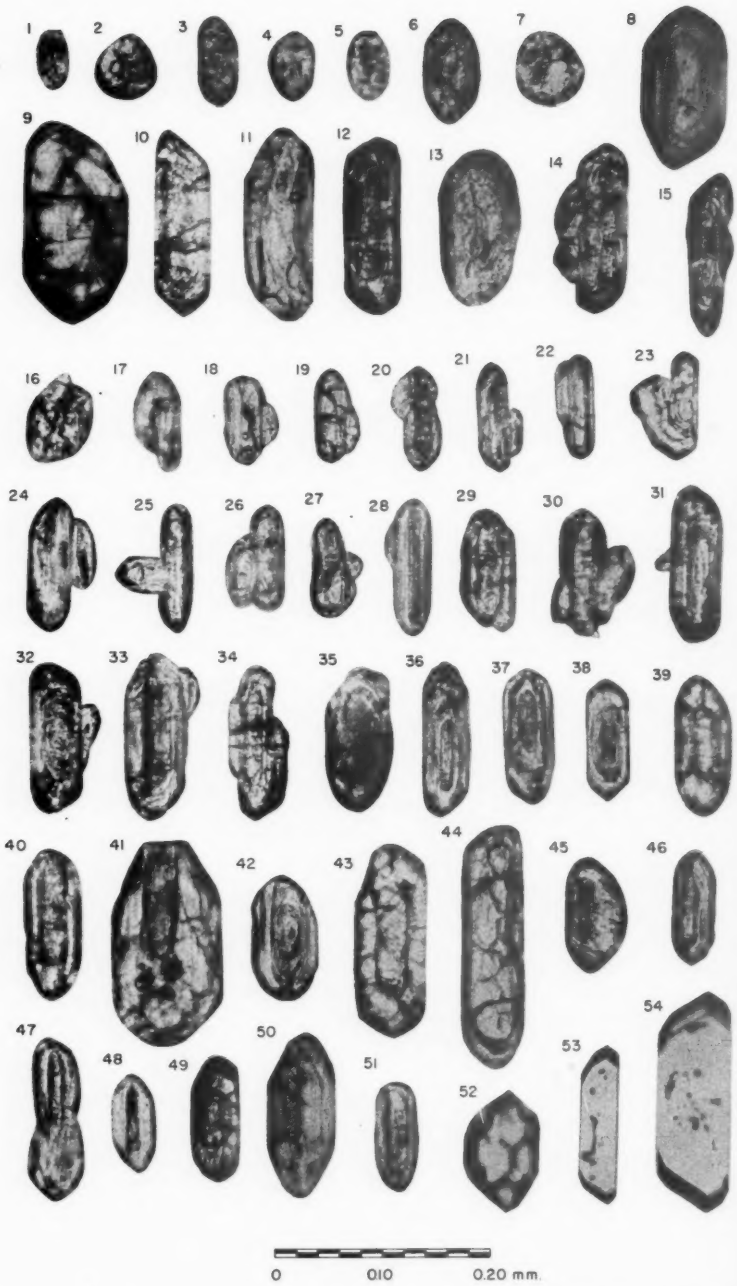


FIGURE 4

FOLIATED GRANITIC GNEISS, POPCORN TEXTURE IN BIOTITE GNEISS, AND STRUCTURAL FEATURES OF HIGHLY CONTORTED MIGMATITE



COMPOSITE PHOTOMICROGRAPH ILLUSTRATING ZIRCON CHARACTERISTICS

apparent closure of the limbs of nearly 20°. Along the fold axis the escarpment cuts completely through a folded amphibolite stratum to produce an opposing V-shaped outcrop pattern. Minor folds (Pl. 1, fig. 2) are indicated by local reversals of dip and in one place on the west limb by a hook-shaped amphibolite band.

CHRISTMAS LAKE SYNCLINE: The Christmas Lake syncline is indicated by the outcrop pattern of highly contorted, banded migmatite (Pl. 1, figs. 3, 4). The contact between the migmatite and the enclosing pink granitic gneiss is sharp, easily placed within 10 feet on the ground. The pattern is U-shaped, opening toward the south with a maximum limb separation of 1 mile. Although dips of foliation and banding within the lithologic unit do not plot as a syncline, the structure is assumed to be synclinal on the basis of U-shaped outcrop pattern and southward-plunging drag folds. The discrepancy in dips is explained by axial-plane foliation on drag and flow folds, owing to intense contortion.

RELATED FOLD STRUCTURES: No complete anticlinal fold has been mapped in the Quad Creek block or in the Gardner Lake area. D. U. Wise (1957, unpub. Ph.D. thesis, Princeton Univ.) reported several southward-plunging anticlines in the Deep Lake area; field mapping during 1957 in the Line Creek and Lonesome Mountain areas by C. J. Casella and Arie Poldervaart also disclosed southward-plunging anticlinal structures. The absence of an anticline between the Blackstone Lake and False Summit synclines is perhaps explained by the high-angle fault passing through Gardner Lake. The movement would then have been essentially vertical, since there is little displacement of the large mafic dike which passes through Christmas Lake. The possibility also remains that prior to granitization, either during original folding or during later metamorphism, horizontal displacements may have accomplished similar results.

West of the Blackstone Lake syncline, dips suggest that an anticlinal crest is approached, and north of Long Lake there is a concentration of foliation planes with southwesterly dips. The area bordering Long Lake is being studied by Dr. Saurindranath Sen, and preliminary mapping substantiates the existence of an anticline near this position.

East of Christmas Lake, dips are steep, and strikes are nearly due north. This foliation may be parallel to axial planes of drag or flow folds concentrated along the crest of an anticline.

MAFIC DIKES: For this discussion, the mafic dikes are most conveniently divided into two major groups—older metamorphosed and younger unmetamorphosed Precambrian dikes. Each group can be subdivided into a set with northwest trend and one with northeast trend. In both cases the more prominent set trends northwest (Fig. 4).

Metamorphosed dikes with northeast trend follow joints which are sinuous both in plan view and in vertical profiles (Pl. 2, fig. 1). The joints are not continuous in any one horizontal plane, hence the map shows individual arcs completely separated by massive country rocks. This is best illustrated just southeast of Blackstone Lake. In most cases dips change abruptly, commonly ranging completely through 180° within 300 feet; therefore the average dip has to be determined from the map. Using differences in elevation along the course of these

PLATE 3.—FOLIATED GRANITIC GNEISS, POPCORN TEXTURE IN BIOTITE GNEISS, AND STRUCTURAL FEATURES OF HIGHLY CONTORTED MIGMATITE

FIGURE 1.—Corner and sides of exposure in foliated granitic gneiss demonstrating the planar structure characteristic of most outcrops.

FIGURE 2.—Popcorn texture in biotite gneiss developed by growth of plagioclase porphyroblasts.

FIGURE 3.—Massive amphibolite block surrounded by contorted migmatite. Original foliation of the block is at acute angle to flow foliation.

FIGURE 4.—Exposure in Christmas Lake cirque demonstrating the contrast in structures produced by the alternating thin bands having flowed and the underlying massive strata having broken into individual blocks.

PLATE 4.—COMPOSITE PHOTOMICROGRAPH ILLUSTRATING ZIRCON CHARACTERISTICS

Composite of photomicrographs illustrating morphological characteristics of zircon crystals. Zircons 1–13 rounded, 14–35 show outgrowths, 36–51 have overgrowth shells, 52–54 euhedral crystals from Laramide porphyry.

dikes, one sees that the two dikes just south of Blackstone Lake dip toward each other at angles of approximately 60°, and the two dikes cropping out in the extreme northwest section of the map dip toward each other at nearly the same angle. Dikes which follow this pattern and trend range in thickness from 2 to 15 feet, with an average of approximately 5 feet. The northwest-trending metamorphosed dikes are more continuous and thicker, ranging between 10 and 20 feet, with an average thickness of 15 feet. They occupy vertical fractures which are straight and for the most part continuous.

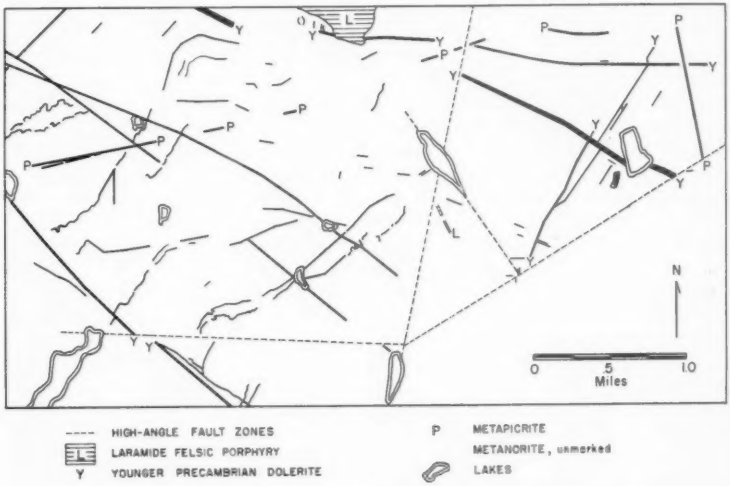


FIGURE 4.—OUTCROP PATTERN OF DIKES IN THE GARDNER LAKE AREA

Two metapicrite dikes (Fig. 4) apparently belong to a different fracture system which trends north-northwest and east-northeast. Both dikes dip at high angles, average 15 feet in thickness, and are apparently discontinuous along strike. The east-northeast dike occupies two nearly parallel fractures along its most westerly extension.

The largest dikes in the region trend northwest and are unmetamorphosed. At Beartooth Butte these dikes are truncated by the Precambrian surface upon which the Middle Cambrian Flathead sandstone was deposited (J. H. Scheufler, 1954, unpub. M.S. thesis, Wayne State Univ.). Dikes of this set range in thickness from 25 to over 100 feet (Pl. 2, fig. 2). Both the dike just northeast of Long Lake and the large dike through Christmas Lake are traceable on photographs for many miles, although they are offset and bifurcate in places. The dikes are for the most part vertical; however, the Christmas Lake dike has a southwesterly dip of approximately 70° near the lake. The northeast-trending unmetamorphosed dikes are essentially vertical and continuous in outcrop. Their average thickness is approximately 10 feet.

The abundance of vertical dikes indicates that the dikes are not related to the forces which produced the southward-plunging folds. All three types of mafic dikes can be found cutting both limbs of plunging synclines. There is no indication that the dikes change dip and strike to conform to the structure of the folds. The metanorite and younger dolerite dikes have similar strike trends but show many differences, as in the sinuous outcrop patterns, discontinuous exposures, lower dips, and metamorphism of the earlier metanorite. The younger dolerites parallel and are normal to the present mountain front; thus they may be interpreted as filling tension fractures produced by uplift of the Beartooth block during Precambrian times. The older metanorites, although they have the same general strike trends, were emplaced at depth and had different structural controls.

OTHER PRECAMBRIAN INTRUSIVES: Metagabbro bodies in the area are emplaced along the axis of the Blackstone Lake syncline. The time of emplacement of the pluglike bodies cannot

be estimated from structural relationships within the area. In lithology and texture they closely resemble the Mae West metagabbro of the Quad Creek block (Eckelmann and Poldervaart, 1957, p. 1232–1233, 1240), which is assumed to have antedated the folding because of the orientation of intrusive pegmatites. The correlation between the synclinal axes and emplacement of these bodies cannot be explained at this time.

One small ultramafic body was found in the Christmas Lake cirque. The 3 by 12 foot lens is conformable and does not exhibit contact effects. The "pod" appears to have been squeezed passively between foliation planes while the rocks were plastic.

Pegmatites are mineralogically simple, consisting for the most part of quartz, microcline, and albite, with associated biotite, ilmenite, and rare muscovite. They are most commonly associated with amphibolite bands and are in most cases conformable to foliation. In massive amphibolites with poor foliation, pegmatites tend to follow jointing, thereby producing irregular-shaped discordant bodies (Pl. 2, fig. 3). Only one large pegmatite was found associated with pink granitic gneiss. This pegmatite is unique in that it also contains 8-inch beryl crystals.

HIGH-ANGLE FAULTS: All structures discussed so far are broken into blocks by high-angle faults. Four of these fault zones are shown on Plate 5, and there are indications of others on aerial photographs. The nearly east-west zone from Long Lake to Losekamp Lake displaces mafic dikes in an apparent left-lateral movement of 500 to 700 feet. The fault zone is marked by sheared rock with local slickensiding. From Losekamp Lake, a displacement zone extends northward through Gardner Lake. This fault zone was first noted when it was found that at a certain point dips on the east limb of the Blackstone Lake syncline changed abruptly. Later mapping revealed discontinuities of mafic dikes along the extension of the zone. Just north of the map area the elevation of the upper contact of the Laramide felsic porphyry crossing this zone from west to east rises abruptly.

A fault zone has been mapped extending the length of Gardner Lake, largely on the basis of topography. This fault is also indicated by the extreme shearing where this zone intersects the northeast-trending fault zone toward the south. The fault from Losekamp Lake, passing south of Christmas Lake, is indicated by the greatly sheared gneiss at the intersection with the Gardner Lake fault, by topographic expression, and by displacement of the large mafic dike through Christmas Lake, together with the metapicrite dike farther east. These displacements are also in an apparent left-lateral direction. Reconnaissance mapping in the Line Creek area to the east indicates that this fault may extend to the front of the Beartooth block. Apparent displacements of mafic dikes along Line Creek have been measured as 900 and 1200 feet in a left-lateral direction. Since dikes displaced along this fault dip at high angles to the west, this apparent displacement can be explained by an essentially vertical movement, the southern side being dropped. Because of the large angles of intersection between faults, a vertical shift is more easily explained than a horizontal one. If the dip of one of the displaced dikes is taken as 75° W., a vertical displacement of about 3500 feet is required to explain an apparent displacement of 900 feet.

Owing to the general absence of Paleozoic and Mesozoic strata, the exact age of the faulting is unknown. The fault through Losekamp and Gardner lakes apparently causes a change in position of the Laramide porphyry; however, the fault may have controlled the emplacement of the intrusive body rather than actually being a displacement of the felsic sheet. The fault south of Christmas Lake appears to be traceable along Line Creek to the front of the Beartooth block, where Paleozoic strata were displaced by Laramide movements.

LARAMIDE FELSIC DIKES: Two exposures of Laramide felsic dikes are indicated on Plate 5—a large, nearly flat sheet north of Beartooth Pass and a 20-foot dike south of Gardner Lake. The larger intrusive mass dips slightly south, perhaps 10°, and is more than 600 feet thick. The intrusion apparently followed jointing in the gneiss, for abrupt thickening and thinning is common. The large unmetamorphosed mafic dike striking west-northwest from Christmas Lake is cut off by this sheet. Slightly north from here, a mafic dike is completely surrounded by felsic porphyry and appears to cut the porphyry. Close examination shows that the porphyry contacts are chilled against the mafic dike, and portions of granitic gneiss are locally still in contact with the mafic dike.

The smaller exposure south of Gardner Lake is vesicular and perhaps represents a feeder to the former surface. If so, it would indicate a minimum cover in this area during intrusion of the Laramide porphyries (*cf.* Eckelmann and Poldervaart, 1957, p. 1231).

General Field Observations

The Gardner Lake area is too far from the metasedimentary border facies for conspicuous variation in abundance of migmatites or resistant bands within the rocks mapped. However, amphibolite layers seem to become more massive to the west. This trend in massiveness is continuous into the Lonesome Mountain area, where it is accompanied by more open folding.

Original folding of sediments into north-south folds was of an open nature, approximating parallel folding with a minimum of flowage. Later, during granitization, increased mobility resulted in renewed deformation, largely of plastic character. The extreme case is illustrated by the contorted migmatite of the Christmas Lake syncline (Pl. 1, figs. 3, 4).

Analysis of Foliation

During field mapping, and later as the data were plotted, it was recognized that dips and strikes of foliation were in many cases not conformable with the general structure of open synclinal folds plunging south. Repeated observations indicated that most of these questionable bedding-plane foliations were steeply dipping, and that their strike was concentrated in a northerly direction. Since the principal axial planes in the area are also approximately vertical and trend north, it was suspected that the conflict was due to axial-plane foliation caused by drag along limbs of folds (Pl. 2, fig. 4).

It was observed in the field that in the highly contorted banded migmatites of the Christmas Lake syncline, banding commonly paralleled the synclinal axis because of directed flowage. The result of mapping the contorted migmatite has been an outcrop pattern indicating a southward-plunging syncline, but foliation measurements suggested only near-vertical beds striking north.

On the assumption that foliation in the contorted migmatite did represent axial-plane foliation, correlation between this direction and

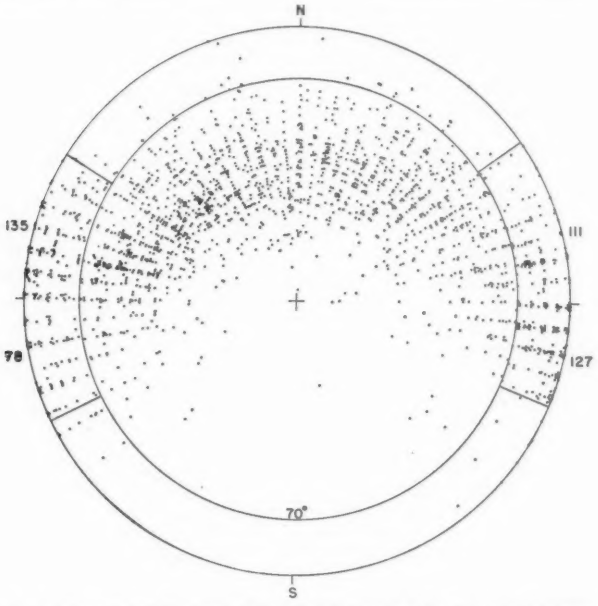


FIGURE 5.—SCHMIDT NET PLOT OF POLES OF FOLIATION PLANES IN GRANITIC GNEISSES

One thousand, nine hundred and twenty-five planes taken throughout the mapped area. Data are reported using 90 per cent of the data as statistically significant. Poles plotted on lower hemisphere.

451 planes dip >70°, with average dip of 88° west.
205 planes dip north, 246 planes dip south.

1282 planes dip <70°, with average dip of 40° south.
721 planes dip southeast, 561 planes dip southwest.

the disharmonious dips and strikes throughout the area was attempted. Poles of all foliation planes recorded in the field were plotted on a single Schmidt net, and an additional 200 axial planes were measured and plotted on separate Schmidt nets. The latter 200 measurements were confined to the highly contorted migmatite, in which only drag- or flow-fold pairs consisting of anticline and syncline were recorded.

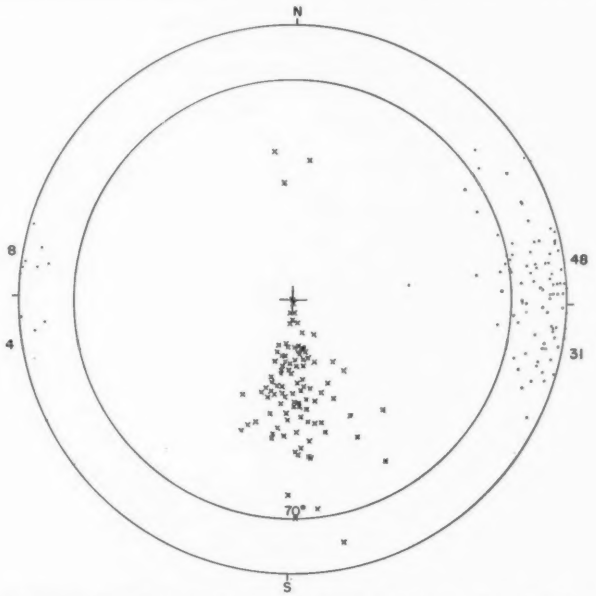


FIGURE 6.—SCHMIDT NET PLOT OF POLES AND PLUNGE AXES OF DRAG OR FLOW FOLDS IN HIGHLY CONTORTED BANDED MIGMATITE, WEST LIMB OF CHRISTMAS LAKE SYNCLINE

Dots represent 100 poles of axial planes measured on drag or flow folds. Crosses represent plunge of axes of drag or flow folds. Poles plotted on lower hemisphere.

91 axial planes dip >70°, with average dip of 82° west.
35 axial planes dip north, 56 axial planes dip south.
Average plunge of fold axes is 65° south.

Foliation planes (Pl. 3, fig. 1), plotted throughout the area, show a well-defined pattern (Fig. 5). With the information already available, the pattern can be interpreted only as a southward-plunging structure consisting of one or more synclines and/or anticlines. The average plunge is well established at 40° S., the dips steepening on the limbs.

Plots of axial planes and axial plunge of drag or flow folds in the contorted migmatite also produced a significant pattern. On both limbs of the syncline the axial planes are concentrated at dips of more than 70° and indicate strikes within 20° of due north. The dips unbalanced toward the west average to approximately 83° W. One hundred measurements of axial plunge of minor folds on the west limb of the migmatite are centered at 65° S. (Fig. 6), whereas the axial plunges of folds on the east limb form a north-south belt on the net with no significant mean plunge (Fig. 7).

Since most axial planes of the contorted migmatite dip more than 70°, this figure was chosen as a possible dividing point between true bedding-plane dips and axial-plane foliation. This limit was therefore set on the Schmidt nets, and possible trends were based on this division.

Of axial planes dipping more than 70°, it was found in the contorted migmatite that 104 dipped south and 68 dipped north. Since the structure is assumed to be an open, southward-plunging fold, the 68 poles cannot represent true bedding-plane directions, as this would require a northward-plunging fold.

The axial plunge of minor folds on the western limb agrees with other observations, but the widely distributed plunge of axes on the eastern limb poses a problem. Two suggestions are

offered: the folds represent plastic deformation after the major syncline was formed, hence are not entirely controlled by the original plunge, or fault blocks in the eastern limb were rotated by Laramide movements. The writer favors the

of the fold axis or axes appears to be a few degrees west of due north. Foliation planes dipping more steeply than 70° present a picture quite similar to that shown by the axial-plane foliation of the contorted migmatite. There is a

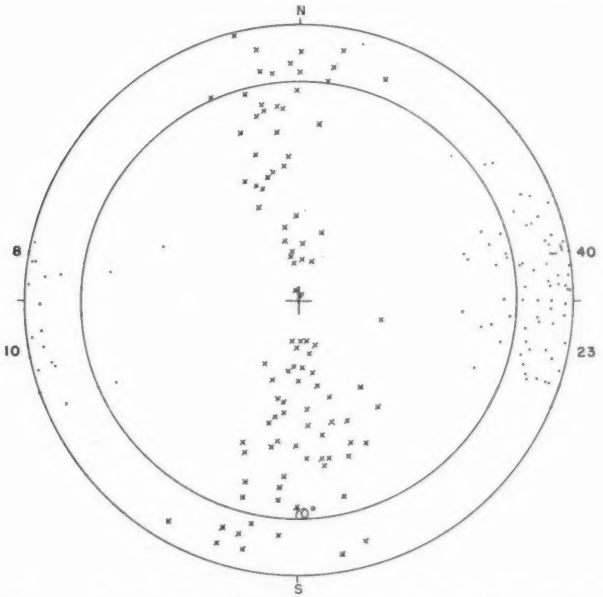


FIGURE 7.—SCHMIDT NET PLOT OF POLES AND PLUNGE AXES OF DRAG OR FLOW FOLDS IN HIGHLY CONTORTED BANDED MIGMATITE, EAST LIMB OF CHRISTMAS LAKE SYNCLINE

Dots represent 100 poles of axial planes measured on drag or flow folds. Crosses represent plunge of axes of drag or flow folds. Poles plotted on lower hemisphere.

81 axial planes dip >70°, with average dip of 83° west.
33 axial planes dip north, 48 axial planes dip south.

first because of the constant strike direction of the planes, and because only one fault plane has been noted.

If 70° is used as the uppermost limit of true bedding-plane dips, the plot of 1925 foliation planes recorded makes a consistent pattern which explains the originally anomalous strikes and dips. Taking 90 per cent as statistically significant, the following observations and conclusions seem justified. A total of 1282 foliation planes dipping less than 70° fall entirely into the northern hemisphere, indicating only southerly dipping beds. Planes with dips of less than 70° are divided between the southeast and southwest, suggesting both limbs of a single open fold, or two or more folds. The average plunge of the fold or folds is 48° S.; dips increase on both limbs to approximately 60°. The strike

good balance between north- and south-dipping planes, suggesting doubly plunging folds which are not verified by the lower dips. The conclusion reached is that generally dips greater than 70° represent axial-plane foliation produced by minor isoclinal drag or flow folding (Pl. 2, fig. 4).

PETROGRAPHY

General Statement

Lithologic divisions have been based on mappable units in the field. Thin sections of all specimens were carefully examined. Thirty samples were selected as representative of rock units recognized in the field, and their mineralogy was measured quantitatively. No attempt has been made to redistribute the lithologic units

as a result of petrographic examinations. While chemical and mineralogical compositions range widely within any particular rock division, there is a consistent trend in direction of change for such measurements as index of refraction and extinction angles of plagioclase and specific gravity and ratio of microcline to plagioclase.

TABLE 1.—PETROGRAPHIC DATA—GRANITIC GNEISSES

Index	Pink Leucogranitic Gneiss						Gray Granitic Gneiss				
	217/55	72/55	Z-3	257/55	29/55	28/55	205/55	116/55	187/55	74/55	Z-6
Quartz	29.8	41.5	30.6	34.1	40.2	36.1	36.7	38.1	28.0	38.6	38.0
Microcline	41.0	37.6	28.8	17.8	16.4	15.5	22.6	19.8	11.8	10.3	10.3
Plagioclase	25.0	20.2	37.4	45.8	40.9	44.4	38.5	38.6	50.9	46.0	47.4
Biotite	0.2	0.2	1.2	0.4	0.7	0.8	0.5	1.1	6.3	2.8	2.3
Chlorite	0.3	..	0.6	0.2	1.0	1.9	0.2	0.3	..	..	0.3
Sericite	2.8	0.3	0.7	0.9	0.4	0.3	1.3	1.2	1.7	1.5	1.0
Opaque minerals	0.3	0.2	0.7	0.7	0.2	0.7	0.1	0.5	1.0	0.8	0.4
Apatite	..	..	..	..	0.1	..	0.1	..	..	..	..
Zircon	..	..	..	0.1	..	..	..	0.1	0.1	..	0.2
Epidote	0.6	..	..	..	0.1	0.2	..	0.3	0.2	..	0.1
Allanite	..	..	..	..	..	0.1	..	..	..	..	..
Sp. gr. (meas.)	2.60	2.59	2.62	2.62	2.62	2.62	2.61	2.64	2.65	2.63	2.64
Sp. gr. (calc.)	2.61	2.61	2.63	2.64	2.63	2.64	2.63	2.64	2.67	2.65	2.65
Biotite, β	1.613	1.602	1.630	1.633	1.608	1.604	1.606	1.610	1.609	1.609	1.634
Plagioclase, β	1.532	1.533	1.532	1.536	1.534	1.533	1.540	1.535	1.536	1.540	1.535
Extinction angle albite twins	17°	13°	16°	8°	16°	18°	4°	6°	5°	6°	14°
Plagioclase, An*	5–7	6–10	5–8	9–14	7–8	6–6	16–17	8–12	9–7	15–12	8–9

* First figure based on β, second based on albite extinction angle

Rock Types

GRANITIC GNEISSES: Two varieties of granitic gneiss have been mapped—a pink leucogranitic gneiss and a gray gneiss. Their mineralogy is similar, and variations are due primarily to changes in abundance of individual minerals. Modes are given in Table 1.

The pink leucogranitic gneisses contain less than 5 per cent mafic minerals and have low specific gravities, averaging 2.62. Microcline content is 15–41 per cent with a complementary variation in plagioclase. The composition of plagioclase ranges from 5 to 14 per cent anorthite, with an average of An_7.

The gray granitic gneisses have approximately 5 per cent mafic minerals and an average specific gravity of 2.64. Microcline abundance ranges from 10 to 25 per cent with corresponding variations in plagioclase. Plagioclase ranges from An_7 to An_{17}, with an average of An_{11}.

Principal minerals in both groups are quartz, microcline, and plagioclase, with minor amounts of biotite, sericite (including muscovite), opaque minerals, apatite, zircon, epidote, allanite, and chlorite. Opaque minerals are magnetite and ilmenite.

The plagioclase is twinned on the albite law, with associated pericline and complex twins. Bent plagioclase crystals with curved lamellae are fairly common, and healed fractures are also observed. The plagioclase has been altered to sericite and kaolin. Myrmekite and clear albite rims are associated with replacements of plagioclase by microcline. The microcline is unaltered, generally nonperthitic, and has well-developed grid twinning. Chlorite is present in rocks of both groups, its abundance being related to the percentage of ferromagnesian minerals.

BIOTITE GNEISSES: The biotite gneisses have been divided into two groups; biotite-rich gneisses with white porphyroblastic plagioclase,

and biotite gneisses with pink porphyroblasts of microcline. These rock types grade into one another and apparently represent a replacement series. The gneiss with white porphyroblasts has a striking texture on weathered surfaces and was called "popcorn" gneiss in the field (Pl. 3, fig. 2). Modes are given in Table 2.

Table 2.—Petrographic Data—Biotite Gneisses, Migmatites, and Metasediments

Index	Biotite Gneisses					Migmatites			Metasediments
	239/55	Z-7	210/55	87/55	Z-9	313/56	314/56	315/56	Z-10
Quartz	34.6	32.7	35.1	12.8	23.4	30.2	42.0	43.1	34.9
Microcline	20.8	19.9	17.5	9.3	0.7	21.8	12.4	0.7	0.9
Plagioclase	40.2	41.0	41.8	59.4	62.1	40.9	38.9	33.3	56.1
Biotite	3.5	4.7	3.5	16.9	11.0	6.1	5.7	21.3	2.8
Chlorite	..	..	..	..	..	..	..	..	0.5
Sericite	0.8	1.0	0.7	0.1	1.3	0.4	0.4	..	2.7
Opaque minerals	..	0.2	1.4	1.0	0.9	0.4	0.3	0.1	0.2
Apatite	0.1	0.2	..	0.1	0.5	..	0.1	0.4	1.2
Zircon	..	0.1	..	0.2	..	..	..	0.1	..
Sphene	..	0.1	..	0.1	..	..	..	..	..
Epidote	..	0.1	..	0.1	0.1	..	..	0.9	0.7
Allanite	..	..	..	..	..	0.2	0.2	0.1	..
Sp. gr. (meas.)	2.64	2.64	2.63	2.68	2.70	2.61	2.63	2.71	2.63
Sp. gr. (calc.)	2.64	2.64	2.65	2.70	2.69	2.64	2.65	2.72	2.66
Biotite, β	1.616	1.638	1.612	1.634	1.638	1.622	1.626	1.632	1.634
Plagioclase, β	1.542	1.544	1.538	1.545	1.546	1.536	1.546	1.550	1.546
Extinction angle albite twins	1°	3°	4°	0°	2°	10°	3°	14°	12°
Plagioclase, An*	18–20	19–18	14–17	22–20	23–21	9–13	23–22	33–31	23–28

* First figure based on β, second based on albite extinction angle

Biotite gneiss with pink porphyroblasts has an average specific gravity of 2.64, with a microcline abundance ranging from 17 to 21 per cent. Ferromagnesian minerals average slightly more than 5 per cent, with biotite as the largest contributor. The composition of the plagioclase is close to An_{18}.

Biotite gneiss with white plagioclase porphyroblasts has a specific gravity of 2.69, with a small amount of microcline (less than 9 per cent). Ferromagnesian minerals amount to as much as 19 per cent, biotite making up the bulk. The plagioclase has a composition of nearly An_{22}.

The two units contain the same minerals, the varieties being determined by differing ratios of various minerals only. The major constituents are quartz, microcline, plagioclase, and biotite, with minor sericite, opaque minerals, apatite, zircon, sphene, and epidote, and traces of allanite and chlorite. Plagioclase is twinned on the albite law with less common pericline and complex twinning. Some crystals are bent, as seen by curved twin lamellae. Breakdown of plagioclase into sericite and kaolin is less widespread than in the granitic gneisses, and albite rims and myrmekite are not as abundant.

Migmatites: The migmatites represent stages in the replacement of original rock types. Thus they do not have distinctive mineralogical compositions. The contorted migmatite of the Christmas Lake area can be separated into three phases: massive biotite-rich bands and blocks (specimen 315/56), gray-shadow migmatite (314/56), and granitic-looking bands (313/56). Specimen 313/56 is similar to the granitic gneisses in appearance and mineralogy. Specimen 314/56 best fits with the group of biotite gneisses, and specimen 315/56 is intermediate between the biotite gneisses and the amphibolites.

The rocks display all features found in the gneisses, such as myrmekite, albite rims, sutured contacts, bent plagioclase, and strained quartz.

METASEDIMENTS: The banded plagioclase-quartz gneiss is closest to nongranitized sediment. Sedimentary banding is prominent, and introduced microcline is low. The rock is nearly white in the hand specimen with faint bands richer in biotite. The composition of the plagioclase is about An_{25}, and the specific gravity averages 2.64. The rock has been completely recrystallized and has a microscopic texture similar to that of the granitic gneisses.

AMPHIBOLITES: The amphibolite units have been subdivided in the field on the basis of foliation and structural relationships. The break between gneiss and amphibolite was placed for mapping purposes at the point where porphyroblastic feldspar development could be recognized. In general, the amphibolite bodies are massive with fair to poor foliation. In several instances lineation of hornblende was the only recognizable structure. The subdivision into para- and ortho-amphibolite is based entirely upon field relationships and texture. Well-foliated and structurally conformable sheets have been classified as para-amphibolite, whereas plug-shaped bodies lacking mineral orientation are designated as ortho-amphibolite. Difficulties in trying to determine their origin by mineralogy and trace elements are discussed by Eckelmann and Poldervaart (1957, p. 1251), Wilcox (1955), and Wilcox and Poldervaart (1958).

In the para-amphiholites, microcline is observed only in thin sections and averages less than 1 per cent, with specific gravities of approximately 2.86, ranging from 2.80 to 2.90. Ferromagnesian minerals make up about 40 per cent, with hornblende and biotite the most abundant. Plagioclase has the composition An_{30}. Principal minerals are quartz, plagioclase, hornblende, and biotite. Minor constituents are microcline, sericite, opaque minerals, apatite, zircon, sphene, epidote, and allanite. Plagioclase is partly altered to sericite and kaolin and twinned after the albite law, with less prominent pericline and complex twins. Myrmekite and albite rims in plagioclase are less common than in the gneisses. Modes are given in Table 3.

Ortho-amphibolites contain no recognizable microcline and average less than 10 per cent quartz. Plagioclase ranges from 0 to 30 per cent. Ferromagnesian minerals constitute the bulk of the rocks, the major minerals in order of abundance being hornblende, plagioclase, biotite, and quartz. Accessory minerals are sericite, opaque minerals, apatite, zircon, sphene, epidote, and allanite. Replacement has produced a fine intergrowth of quartz in hornblende. The

TABLE 3.—PETROGRAPHIC DATA—PARA-AMPHIBOLITES AND ORTHO-AMPHIBOLITES

Index	Para-amphibolites			Ortho-amphibolites		
	Z-5	Z-8	92/55	134/55	135/55	153/55
Quartz	16.6	16.9	31.3	10.7	..	9.8
Microcline	3.0	0.1	0.1	..	..	..
Plagioclase	36.0	38.2	31.9	1.3	..	29.6
Hornblende	25.8	27.9	22.9	83.5	71.0	45.7
Biotite	11.0	8.9	11.1	0.1	28.0	8.7
Sericite	0.6	1.6	..	2.1	..	4.1
Opaque minerals	1.2	1.6	0.4	0.3	0.8	1.5
Apatite	0.5	0.8	0.1	..	0.1	0.4
Zircon	0.2	..	0.1	0.1	..	..
Sphene	1.2	1.3	0.2	..	0.1	..
Epidote	3.8	2.4	1.7	1.8	..	0.2
Allanite	0.1	0.3	0.2	0.1	..	..
Sp. gr. (meas.)	2.88	2.90	2.80	3.04	3.03	2.91
Sp. gr. (calc.)	2.88	2.89	2.83	3.20	3.22	2.98
Hornblende, γ	1.667	1.672	1.671	1.667	1.652	1.666
Hornblende, 2V(−)	75°	65°	82°	72°	88°	74°
Biotite, β	1.610	1.632	1.631	..	1.626	1.637
Plagioclase, β	1.546	1.550	1.548	1.548	..	1.560
Extinction angle albite twins	13°	15°	14°	8°	..	30°
Plagioclase, An*	23–28	33–32	30–31	30–27	..	55–52

* First figure based on β, second based on albite extinction angle

average specific gravity is greater than 3.00, ranging from 2.91 to 3.22. The plagioclase ranges from An_{27} to An_{55}.

MAFIC DIKES: Postgranitization dikes are abundant throughout the area. The dikes have been divided into two groups; metamorphosed picrite and norite dikes, and unaltered quartz dolerites. The two groups display distinct field relationships and are of different age. Modes are given in Table 4.

Metamorphosed dikes are characterized by strong clouding of pyroxene and plagioclase (Poldervaart and Gilkey, 1954; Murthy, 1958), olivine with coronas of radial enstatite, and granoblastic texture of pyroxene due to recrystallization. Hand specimens generally display a fresh, unaltered appearance.

The metapicrite intrusive rocks are coarse-grained with plagioclase, olivine, and clinopyroxene as the principal minerals. Hornblende and biotite together make up 15 per cent of the

rock, and opaque minerals contribute approximately 4 per cent. The specific gravity is approximately 3.20. Concentration of secondary magnetite which fills shear fractures normal to the plane of the dike locally gives a strong magnetic field.

TABLE 4.—PETROGRAPHIC DATA—METAPICRITE, METANORITE, AND QUARTZ DOLERITE

Index	Metapicrite	Metanorite		Quartz-dolerite
	288/56	290/56	149/55	11/55
Quartz	..	..	0.3	3.5
Plagioclase	18.7	28.0	46.0	48.5
Olivine	24.4	11.5	..	..
Clinopyroxene	36.7	51.2	32.6	30.3
Orthopyroxene	..	0.5	9.7	2.1
Hornblende	7.9	..	..	3.7
Biotite	7.1	2.3	2.6	0.6
Sericite	..	..	..	0.5
Opaque minerals	3.9	6.5	4.8	9.4
Apatite	..	..	..	0.1
Chlorite	1.3	..	4.0	1.3
Sp. gr. (meas.)	3.20	3.06	3.03	3.02
Sp. gr. (calc.)	3.17	3.15	3.00	3.01
Olivine, γ	1.74	1.72	..	..
Olivine, 2V(−)	72°	83°	..	..
Clinopyroxene, γ	1.71	1.698	1.700	1.71
Clinopyroxene, 2V (+)	54°	<68°	39°	57°
Biotite, β	1.618	1.614	1.626	1.618
Plagioclase, β	..	1.556	1.562	1.559
Extinction angle albite twins	..	28°	29°	33°
Plagioclase, An*	..	46–50	56–52	53–57

* First figure based on β, second based on albite extinction angle

The metanorites typically have a megascopic doleritic texture of lath-shaped plagioclase crystals which average An_{51}. Opaque minerals make up 5 per cent of the rock, but strong magnetic properties were not observed.

The younger quartz dolerite dikes are the largest in the area and have a fresh appearance in hand specimens and thin sections. Quartz is an original constituent. The rock contains less than 48 per cent ferromagnesian minerals with more than 9 per cent magnetite. The dikes produce inclinations on a dip needle of several degrees but do not affect a Brunton compass. The plagioclase is not clouded and has a composition of An_{55}. Micropegmatite makes up a significant portion of the rock but is restricted to areas between large plagioclase laths.

PEGMATITES: The pegmatites of the area are characteristically microcline and quartz with associated albite, ilmenite, biotite, muscovite, and in one instance large beryl crystals. The pegmatites are of two structural types, distinctive lenses generally conformable with the foliation in the surrounding rocks, and discordant bodies, filling joints and replacing the adjoining rocks. The presence or absence of foliation in the country rocks appears to be the controlling factor, as the mineralogy is identical in both types. Feldspar crystals commonly are up to 6 inches long and mica books are in many places hand-size. Ilmenite nodules as large as golf balls are found in most of the larger bodies. The beryl-bearing pegmatite is unique, in that it occurs in granitic gneiss and contains feldspar crystals more than a foot long, muscovite books 8 inches across, and small amounts of smoky quartz associated with beryl, crystals of which are up to 10 inches long.

ULTRAMAFIC ROCK: The principal mineral of the ultramafic body is actinolite with associated phlogopite, opaque minerals, chlorite, and antigorite.

MINERALOGY

Mineral Analyses

Three hornblendes and three biotites were separated from the gneisses and amphibolites by the use of heavy liquids and magnetic separator. The minerals were chemically analyzed and their formulas calculated (Table 5). This step was taken as the beginning of a program of mineral separations and analyses to get more information concerning mineral phases in addition to the bulk compositions of rocks. The hornblendes Z-5 and RH 134-55 are remarkably similar in composition, as are the biotites Z-7 and Z-9; however, little can be said about possible mineralogical trends with so few control points. With the exception of hornblende sample RH 135-55, the analyses are comparable to those reported by Larsen and Draisin (1950) from the rocks of the southern California batholith and Rosenzweig and Watson (1954) from the Piedmont region of Pennsylvania and Dela-

ware. Larsen and Draisin reported trends in the Al_2O_3, MgO, and FeO content of the biotites and systematic variations of FeO and MnO, MgO, and Fe_2O_3 content of hornblende when plotted on a Larsen variation diagram. Rosenzweig and Watson reported a definite correlation of total potassium content and K-Na ratio found in their hornblendes, suggesting a method by which the degree of granitization which has taken place within a region may be estimated.

It thus appears probable that further mineralogical studies coupled with bulk rock analyses and petrographic descriptions will furnish important information concerning the character of the granitizing fluids and their possible variation with time.

TABLE 5.—CHEMICAL ANALYSES AND CALCULATED FORMULAS OF HORNBLENDE AND BIOTITE*

	Hornblende			Biotite			
	Z-5	RH 134–55	RH 135–55	Z-7	Z-9	RH 135–55	RH 135–55†
SiO_2	45.48	47.54	54.70	36.60	36.48	42.96	38.98
TiO_2	.95	.97	.11	2.66	2.66	1.05	1.36
Al_2O_3	9.39	7.81	4.01	16.86	16.80	11.55	14.05
Fe_2O_3	6.17	5.99	2.96	5.95	5.39	4.72	5.31
FeO	10.71	10.02	6.12	15.10	15.89	10.59	12.04
MnO	.42	.23	.19	.30	.22	.19	.19
MgO	12.49	13.25	18.55	10.27	10.05	16.65	15.99
CaO	10.54	11.04	11.16	.02	.02	2.82	.03
Na_2O	1.09	1.20	.54	.51	.63	.33	.27
K_2O	.84	.84	.23	9.23	8.92	6.34	8.37
H_2O^+	2.20	1.62	2.06	2.59	2.38	2.60	2.77
H_2O^-	.30	.02	nil	.10	.02	.34	.45
F	.08	.01	.02	.16	.12	.20	.25
	100.66	100.54	100.65	100.35	99.58	100.34	100.06
Less O for F	.03	..	.01	.07	.05	.08	.10
	100.63	100.54	100.64	100.28	99.53	100.26	99.96

	Hornblende
Z-5	$(OH_{2.14}F_{.04})(Ca_{1.65}Na_{.31}K_{.16})(Mg_{.05}Fe^{+3}_{.68}Fe^{+2}_{1.31}Ti_{.10}Al_{.27}Mn_{.03})(Si_{6.65}Al_{1.35})O_{21.82}$
RH 134–55	$(OH_{1.58}F_{.01})(Ca_{1.73}Na_{.34}K_{.16})(Mg_{2.88}Fe^{+3}_{.66}Fe^{+2}_{1.22}Ti_{.11}Al_{.29}Mn_{.03})(Si_{6.94}Al_{1.06})O_{22.41}$
RH 135–55	$(OH_{1.91}F_{.01})(Ca_{1.66}Na_{.14}K_{.04})(Mg_{3.85}Fe^{+3}_{.31}Fe^{+2}_{.71}Ti_{.01}Al_{.27}Mn_{.02})(Si_{7.62}Al_{.38})O_{22.08}$
	Biotite
Z-7	$(OH_{1.32}F_{.04})(Ca_{tr.}Na_{.08}K_{.90})(Mg_{1.17}Fe^{+3}_{.34}Fe^{+2}_{.96}Ti_{.15}Al_{.32}Mn_{.02})(Si_{2.80}Al_{1.20})O_{10.64}$
Z-9	$(OH_{1.22}F_{.02})(Ca_{tr.}Na_{.09}K_{.88})(Mg_{1.16}Fe^{+3}_{.31}Fe^{+2}_{1.03}Ti_{.15}Al_{.34}Mn_{.01})(Si_{2.82}Al_{1.18})O_{10.74}$
RH 135–55†	$(OH_{1.39}F_{.06})(Ca_{tr.}Na_{.04}K_{.80})(Mg_{1.79}Fe^{+3}_{.30}Fe^{+2}_{.76}Ti_{.08}Al_{.17}Mn_{.01})(Si_{2.93}Al_{1.07})O_{10.55}$

* Analyses by Hugo B. Wiik

† Recalculated for hornblende impurity

Temperatures

Muscovite from the pegmatite in the Christmas Lake cirque was run for Na and K content using a flame photometer (Heinrich D. Holland, 1956, personal communication). In addition, Holland forwarded the samples to S. Goldich for alkali determinations. The results of both investigations are tabulated with temperatures determined from the curve by Eugster and Yoder (1955, p. 125) and Eugster (1956).

	Holland-Moore	*Goldich*
Na	1.59 ± 0.03	0.67
K	7.9 ± 0.4	8.53
Rb	..	0.42
Cs	..	0.01
Temperature	445° C.	480° C.

Grootemaat and Holland (1955) reported similar determinations on muscovite from the Peerless pegmatite, Black Hills, South Dakota. Temperatures found were 350° C. for the core and 500° C. for the outer zones of the pegmatite. Eckelmann and Poldervaart (1957, p. 1245) discussed the probable temperatures during granitization of the Quad Creek area and arrived at a maximum of 600° C.

TABLE 6.—MORPHOLOGICAL CHARACTER OF ZIRCONS

(Figures are in per cent, based on 400 measurements for each specimen.)

Index	Granitic Gneisses				Migmatites				Metasediments			Pegmatites		Laramide Porphyry
	Z-4	Z-3	Z-6	Z-7	Z-9	190/53	116/53	Z-10	60/53	Z-5	52/53	270/56	16/55	Z-1
Rounded, no outgrowths or overgrowths	50	61	66	73	72	81	89	85	79	47	56	81	80	8
Rounded, with outgrowths	20	17	16	16	20	17	9	14	14	51	43	5	9	2
Rounded, with overgrowths	27	21	17	10	7	2	1	1	6	2	0	14	9	1
Euhedral	3	1	1	1	1	0	1	0	1	0	1	0	2	89

Index Number	
Z-4	Pink leucogranitic gneiss, Gardner Lake area
Z-3	Pink leucogranitic gneiss, Gardner Lake area
Z-6	Gray granitic gneiss, Gardner Lake area
Z-7	Biotite gneiss with pink microcline feldspar porphyroblasts, Gardner Lake area
Z-9	Biotite gneiss with white plagioclase feldspar porphyroblasts, Gardner Lake area
190/53	Banded biotite-hornblende migmatite, Quad Creek area
116/53	Banded biotite migmatite, Quad Creek area
Z-10	Banded plagioclase-quartz gneiss, Gardner Lake area
60/53	Quartzite, Quad Creek area
Z-5	Foliated para-amphibolite, Gardner Lake area
52/53	Biotite schist, Quad Creek area
270/56	Pegmatite in pink gneiss, Gardner Lake area
16/55	Pegmatite in amphibolite, Gardner Lake area
Z-1	Laramide felsic porphyry, Gardner Lake area

Age Determinations

Rb-Sr and K-A ages were determined at the Lamont Geological Observatory for five samples from the Quad Creek and Gardner Lake areas and for two biotites from near-by mountain blocks. Numbers obtained from these seven samples agree within the experimental error and indicate an age of approximately 2750 million years for the granitic gneisses and pegmatites surrounding the Bighorn Basin (Gast, Kulp, and Long, 1958).

Zircon Studies

A series of 14 samples was collected representing all rock types, except mafic intrusive rocks. The specimens were crushed, and zircons separated by a standardized technique (Larsen and Poldervaart, 1958, p. 550-553; Eckelmann and Poldervaart, 1957, p. 1229) using jaw crusher, disk grinder, bromoform, Frantz magnetic separator, and an acid leach. The number of zircon crystals recovered ranged, depending on the rock type, from a few hundred to several thousand crystals. In all cases the total crop was mounted in balsam on glass slides.

Measurement and observations of crystals were conducted in a systematic manner along equally spaced traverses across the entire surface of the slide. This grid pattern was established using a Chayes point counter. Length and width of zircons were measured with an ocular micrometer which can be read to within 0.002 mm. The lengths and widths of 200 unbroken crystals were recorded for each sample, and the derived ratios are based on these measurements. Observations of the morphological character of zircons were made on 400 crystals of each sample.

Zircons obtained from each rock type were studied using a magnification of 180×. Crystals were divided into four groups; (1) rounded

grains with no outgrowths or overgrowths, (2) rounded grains with outgrowths but not a complete shell, (3) rounded grains with complete overgrowth in the form of one or more separate shells, and (4) euhedral crystals with or without enclosed cores. In most cases the overgrowth material was distinctly lighter in color than the core, commonly purple as opposed to brown for the original rounded grain. Plate 4 is a compilation of photomicrographs illustrating the categories and indicating the nature of the features discussed. The photographs are arranged in groups; 1–13 are rounded without outgrowths or overgrowths, 14–35 display outgrowths, 36–51 have cores with complete overgrowths, and 52–54 are euhedral crystals from a Laramide porphyry (Poldervaart and Eckelmann, 1955).

Table 6 is a tabulation in per cent of 400 observations of morphological characters, made for each specimen. The granitic gneisses have a higher percentage of overgrown cores than the other rock types. Both metasediments and migmatites have numerous grains which exhibit outgrowths but few zircons with complete shells. The pegmatites have a high percentage of rounded grains, which indicates that they were derived in part from the surrounding rocks.

Parameters of the zircon samples are given in Table 7. Measurements are further described graphically in Figure 8, using the method of the reduced major axis. The advantage of this method is that ratios of lengths and widths of various samples can be compared directly, the slope of the reduced major axis being independent of size of the crystals. In most cases differences or similarities can be determined by visual inspection, but further verification can be obtained by simple z tests on slope and position.

The calculations for comparison of slopes and for line position have been worked out for two sets of populations: Z-3 and Z-4, and Z-3 and Z-5. For a discussion and evaluation of the sta-

TABLE 7.—PARAMETERS OF ZIRCON SAMPLES

Index Number	$\bar{x}$ (mm)	$\bar{y}$ (mm)	S_x (mm)	S_y (mm)	a	r
Z-4	.135	.051	.050	.019	.387	.666
Z-3	.123	.047	.054	.020	.360	.766
Z-6	.122	.054	.038	.018	.458	.605
Z-7	.104	.034	.029	.008	.285	.452
Z-9	.119	.052	.065	.025	.383	.743
190/53	.137	.057	.044	.015	.348	.469
116/53	.109	.040	.036	.012	.342	.657
Z-10	.130	.065	.060	.025	.425	.689
60/53	.119	.058	.032	.019	.600	.632
Z-5	.072	.044	.025	.012	.476	.612
52/53	.075	.040	.023	.011	.479	.340
270/56	.102	.053	.035	.020	.577	.765
16/55	.096	.053	.039	.019	.483	.627
Z-1	.155	.056	.071	.026	.371	.752

$\bar{x}$ = mean length
$\bar{y}$ = mean width
S_x = standard deviation of length
S_y = standard deviation of width
r = coefficient of correlation
a = tangent of S_y/S_x

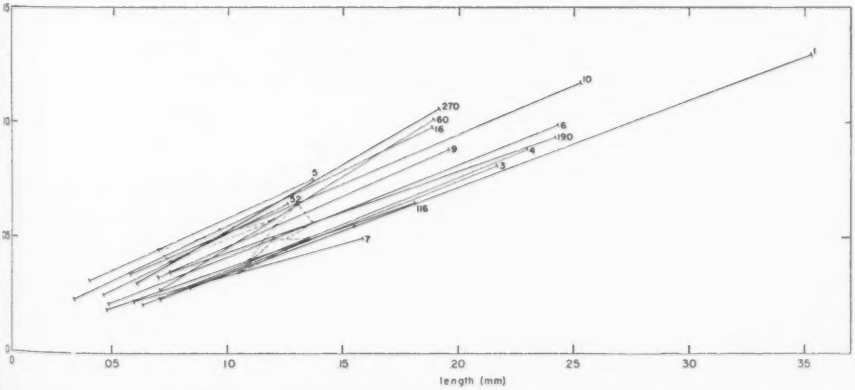


FIGURE 8.—REDUCED MAJOR AXES OF ZIRCON SAMPLES

The three polygons are formed by dashed lines connecting mean lengths and widths of metasediments, migmatites, and gneisses.

TABLE 8.—ANALYSES A

	Pink Leucogranitic Gneiss							Gray Granitic Gneiss				
	217/55†	72/55†	Z-3†	Z-3*	257/55†	29/55†	28/55†	205/55†	116/55†	187/55†	74/55†	Z-6†
SiO_2	74.7	79.4	75.2	74.90	76.3	79.1	77.4	77.1	77.6	72.9	77.4	77.
TiO_2	0.1	0.1	0.2	0.13	0.2	0.1	0.2	tr.	0.1	0.2	0.2	0.
Al_2O_3	14.1	11.2	13.7	14.30	13.7	12.0	12.7	13.4	12.6	14.7	12.8	12.
Fe_2O_3	0.1	0.1	0.3	0.29	0.2	0.1	0.3	0.1	0.2	0.5	0.3	0.
FeO	0.2	tr.	0.2	0.85	0.3	0.1	0.4	tr.	0.3	0.5	0.5	0.
MnO	..	..	..	0.01	..	..	..	..	..	..	..	..
MgO	0.1	0.1	0.5	0.55	0.2	0.4	0.7	0.2	0.4	1.6	0.7	0.
CaO	0.6	0.4	0.6	0.94	1.2	0.7	0.6	1.3	0.9	1.1	1.1	0.
Na_2O	2.7	2.2	4.1	3.47	4.7	4.4	4.9	3.8	4.1	5.4	4.8	5.
K_2O	7.3	6.5	5.2	3.81	3.1	3.1	2.8	4.1	3.6	2.8	2.1	2.
P_2O_5	..	..	..	0.01	..	tr.	..	..	..	..	..	..
ZrO_2	..	..	..	..	tr.	..	..	..	0.1	0.1	..	0.
H_2O^+	0.1	tr.	tr.	0.26	0.1	tr.	tr.	tr.	0.1	0.2	0.1	0.
H_2O^-	..	..	..	0.12	..	..	..	..	..	..	..	..
CO_2	..	..	..	0.00	..	..	..	..	..	..	..	..
	100.0	100.0	100.0	99.64	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.

Index to Chemically Analyzed Specimens

Differentiation Index	*Specimen Number*	*Lithologic Description*
91.5	287/53	leucogranitic gneiss, Quad Creek
89.8	313/56	granitic facies of contorted migmatite, Gardner Lake
89.7	248/53	leucogranitic gneiss, Quad Creek
88.8	Z-3	pink leucogranitic gneiss, Gardner Lake
85.6	Z-6	gray granitic gneiss, Gardner Lake
83.9	Z-7	biotite gneiss with pink microcline porphyroblasts, Gardner Lake
82.4	314/56	gray-shadow facies of contorted migmatite, Gardner Lake
80.5	249/53	tonalitic gneiss, Quad Creek
78.3	Z-10	banded plagioclase-quartz gneiss, Gardner Lake
75.0	176/54	banded biotite-hornblende migmatite, Quad Creek
72.7	Z-9	biotite gneiss with plagioclase porphyroblasts, Gardner Lake

* Chemical analyses by Hugo B. Wiik

† Chemical composition calculated from modal analysis

tistical procedures, see Imbrie (1956) and Larsen and Poldervaart (1958). Samples Z-3 and Z-4 are pink granitic gneisses and were collected within a short distance of each other. Their similarity is indicated by P values of 0.35 and 0.15 for slope and position respectively. In contrast, samples Z-3 and Z-5 are different rock types, Z-5 being a para-amphibolite, and their P values for slope and position are 0.03 and 0.001, indicating a very slight possibility that the differences could be due to chance alone.

While there is no apparent correlation between slope angles, there is a grouping of mean lengths and widths for zircons of the major rock types. On Figure 8, dashed lines have been used to connect mean points for metasediments, migmatites, and gneisses. The zircons of metasediments have a wide range in mean length but tend to be stubby. Gneisses contain longer crystals which have the highest length-width ratios. Zircons of the migmatites occupy an intermediate position. These findings contrast

ED CHEMICAL COMPOSITIONS

Biotite Gneiss with rocline Porphyroblasts			Biotite Gneiss with Plagioclase Porphyroblasts			Contorted Migmatite Facies					
Z-7†	Z-7*	210/55†	87/55†	Z-9†	Z-9*	313/56†	313/56*	314/56†	314/56*	315/56†	315/56*
74.3	72.25	*75.1*	*64.1*	*68.5*	65.86	*74.3*	73.96	*77.3*	73.08	*72.9*	65.60
0.1	0.17	*0.4*	*0.3*	*0.2*	0.33	*0.1*	0.03	*0.1*	0.12	*tr.*	0.44
14.2	15.62	*13.5*	*18.2*	*16.9*	18.26	*13.9*	15.55	*12.3*	15.51	*12.4*	15.32
0.2	0.43	*0.5*	*0.7*	*0.5*	1.23	*0.2*	0.04	*0.2*	0.03	*0.6*	0.91
0.1	1.06	*0.7*	*0.9*	*0.7*	2.34	*0.4*	0.21	*0.3*	0.86	*0.7*	4.75
..	0.01	..	..	..	0.02	..	0.00	..	0.01	..	0.06
1.2	0.64	*0.9*	*4.2*	*2.7*	1.15	*1.6*	0.24	*1.4*	0.50	*5.3*	3.29
1.8	2.07	*1.4*	*2.6*	*2.9*	3.47	*0.9*	1.57	*1.8*	2.53	*2.7*	3.74
3.9	4.16	*4.1*	*5.6*	*5.8*	5.40	*4.3*	3.38	*3.7*	3.57	*2.7*	1.73
3.9	3.14	*3.4*	*3.1*	*1.4*	1.37	*4.2*	5.12	*2.7*	3.11	*2.1*	3.65
0.1	0.01	..	*tr.*	*0.2*	0.03	..	0.02	*0.1*	0.03	*0.2*	0.20
0.1	..	..	*0.1*	..	..	..	..	..	..	*0.1*	..
0.1	0.21	*tr.*	*0.2*	*0.2*	0.42	*0.1*	0.03	*0.1*	0.21	*0.3*	0.77
..	0.03	..	..	..	0.03	..	0.04	..	0.07	..	0.06
..	0.10	..	..	..	0.15	..	0.00	..	0.00	..	0.00
100.0	99.90	*100.0*	*100.0*	*100.0*	100.06	*100.0*	100.19	*100.0*	99.63	*100.0*	100.52

Index to Chemically Analyzed Specimens—Continued

riation dex	*Specimen Number*	*Lithologic Description*
.3	329/53	tonalitic gneiss, Quad Creek
.9	315/56	biotite schist facies of contorted migmatite, Gardner Lake
.4	281/53	banded biotite-hornblende migmatite, Quad Creek
.4	92/55	para-amphibolite, Gardner Lake
.0	57/54	banded biotite-hornblende migmatite, Quad Creek
.8	404/53	banded biotite-hornblende migmatite, Quad Creek
.0	Z-5	para-amphibolite, Gardner Lake
.5	195/53	migmatitic biotite schist, Quad Creek
.3	153/55	ortho-amphibolite, Gardner Lake
.2	227/54	para-amphibolite, Quad Creek
.5	125/53	para-amphibolite, Quad Creek
.1	131/54	para-amphibolite, Quad Creek
.2	111/54	amphibolite, origin not known, Quad Creek
.5	41/53	para-amphibolite, Quad Creek

with zircon data obtained for igneous plutons (Taubeneck, 1957; Alper and Poldervaart, 1957; Larsen and Poldervaart, 1958), which indicate distinct zircon populations within magmatic bodies. It appears significant that zircons from the pegmatites lie with the metasediment group, whereas those of the Laramide porphyry are closest to the gneisses.

These zircon studies seem to permit the following generalizations about this area. The core of the uplift is not a homogeneous intrusive body but a sedimentary pile with complex history. Original sediments ranged from coarse sands to fine dolomitic muds. The size, shape, and character of zircons to be found in any of the major rock units can be predicted with fair accuracy. The pegmatites represent, in part, mobilized country rock which moved only short distances. No trace was found of a silicate melt injected *lit-par-lit* and containing a distinct zircon population.

	Banded Plagioclase-Quartz Gneiss		Amphibolite					Ortho-Amphibolite		
	Z-10†	Z-10*	Z-5†	Z-5*	Z-8†	92/55†	92/55*	134/55†	135/55†	153/55†
SiO_2	*73.3*	73.17	*57.3*	56.80	*56.3*	*65.1*	62.34	*44.1*	*38.3*	*48.9*
TiO_2	*0.1*	0.12	*0.3*	0.95	*0.4*	*0.1*	0.54	*0.1*	*0.2*	*0.4*
Al_2O_3	*15.4*	16.11	*15.3*	15.47	*15.7*	*12.5*	16.94	*10.2*	*12.3*	*16.2*
Fe_2O_3	*0.2*	0.35	*4.8*	2.52	*5.3*	*4.1*	1.91	*13.8*	*12.4*	*8.2*
FeO	*0.2*	0.42	*7.3*	5.05	*7.6*	*5.8*	3.74	*18.8*	*16.8*	*10.9*
MnO	..	0.01	..	0.05	..	..	0.10	..	..	..
MgO	*0.8*	0.37	*4.8*	5.79	*4.6*	*4.7*	3.29	*6.9*	*12.9*	*6.0*
CaO	*3.7*	3.39	*4.9*	5.82	*5.5*	*3.7*	5.43	*5.3*	*4.2*	*5.9*
Na_2O	*5.0*	4.50	*3.1*	3.06	*3.0*	*2.7*	3.54	*0.2*	..	*1.7*
K_2O	*0.7*	0.97	*1.6*	2.41	*1.0*	*1.0*	1.44	*0.3*	*2.5*	*1.3*
P_2O_5	*0.5*	0.03	*0.2*	0.05	*0.3*	*tr.*	0.01	..	*tr.*	*0.2*
ZrO_2	..	..	*0.1*	..	..	*0.1*	..	*0.1*	..	..
H_2O^+	*0.1*	0.48	*0.3*	1.53	*0.3*	*0.2*	0.83	*0.2*	*0.4*	*0.3*
H_2O^-	..	0.02	..	0.07	..	..	0.05	..	..	..
CO_2	..	0.00	..	0.00	..	..	0.00	..	..	..
	100.0	99.94	*100.0*	99.57	*100.0*	*100.0*	100.16	*100.0*	*100.0*	*100.0*

Index to Calculated Compositions

Differentiation Index	*Specimen Number*	*Lithologic Description*‡
97.5	72/55	pink leucogranitic gneiss
95.5	217/55	pink leucogranitic gneiss
95.2	Z-3	pink leucogranitic gneiss
94.9	29/55	pink leucogranitic gneiss
93.9	28/55	pink leucogranitic gneiss
92.6	Z-6	gray granitic gneiss
92.4	257/55	pink leucogranitic gneiss
92.2	205/55	gray granitic gneiss
92.1	116/55	gray granitic gneiss
90.9	74/55	gray granitic gneiss
90.1	313/56	granitic facies of contorted migmatite
88.5	210/55	biotite gneiss with pink microcline porphyroblasts

‡ All specimens from the Gardner Lake area.

Petrogenesis

Introduction

The existence of open folds in the Gardner Lake area places restrictions on the number of possible interpretations for the origin of the rocks. Similar folding within the metasedimentary migmatites and granitic gneisses has been reported by Eckelmann and Poldervaart (1957) and D. U. Wise (1957, unpub. Ph.D. thesis, Princeton Univ.). In all cases the deformation is characterized by simple folds plunging southward.

The geologic map shows three synclinal structures trending north-south and plunging 40° S. These structures are indicated by V-shaped outcrop patterns opening to the south and by strike and dip of foliation planes and tabular rock bodies. The large amount of amphibolitic material in conformable layers leaves little doubt that the area is composed of folded strata

Continued

Metapicrite and Metanorite Dikes							Quartz Dolerite Dikes	
56†	288/56*	1/55*	290/56†	290/56*	149/55†	149/55*	11/55†	11/55*
.3	48.23	42.14	*45.9*	47.32	*49.2*	49.86	*48.3*	50.68
.5	0.52	0.28	*0.8*	0.65	*0.6*	0.73	*1.4*	2.22
.4	6.89	6.61	*12.1*	12.36	*19.6*	14.63	*17.0*	13.06
.0	2.12	5.88	*5.8*	2.65	*4.1*	2.74	*6.6*	3.96
.1	13.17	5.26	*7.5*	9.28	*4.1*	8.49	*7.0*	12.31
	0.17	0.11	..	0.18	..	0.17	..	0.23
.8	18.53	27.72	*12.6*	16.80	*7.5*	10.66	*5.0*	4.29
.0	7.04	4.78	*13.4*	7.59	*11.6*	8.62	*11.7*	8.18
.0	2.43	0.61	*1.7*	1.84	*2.6*	2.32	*2.6*	2.36
.8	0.94	0.16	*0.2*	0.44	*0.6*	0.61	*0.3*	1.13
	0.03	0.05	..	0.13	..	0.17	*0.1*	0.02
	..	..	..	..	..	..	..	..
.1	0.01	6.75	*tr.*	1.09	*0.1*	0.80	*tr.*	1.40
	0.09	0.10	..	0.10	..	0.08	..	0.10
	0.05	0.00	..	0.00	..	0.00	..	0.00
.0	100.22	100.45	*100.0*	100.43	*100.0*	99.88	*100.0*	99.94

Index to Calculated Compositions—Continued

viation dex	*Specimen Number*	*Lithologic Description*‡
.4	239/55	biotite gneiss with pink microcline porphyroblasts
.2	187/55	gray granitic gneiss
.9	314/56	gray-shadow facies of contorted migmatite
.4	Z-7	biotite gneiss with pink microcline porphyroblasts
.3	Z-10	banded plagioclase-quartz gneiss
.6	Z-9	biotite gneiss with white plagioclase porphyroblasts
.5	87/55	biotite gneiss with white plagioclase porphyroblasts
.3	315/56	biotite schist facies of contorted migmatite
.2	92/55	para-amphibolite
.4	Z-5	para-amphibolite
.6	Z-8	para-amphibolite
.3	153/55	ortho-amphibolite
.0	135/55	ortho-amphibolite
0	134/55	ortho-amphibolite

fied rocks. This observation is supported by independent lines of evidence such as zircon studies, presence of undoubted metasediments, and the preservation of axial-plane foliation produced by drag or flow folds in metasediments.

Intercalated with the stratified rocks are layers and lenses of conformable granitic gneisses. Possible explanations for these structures which may be considered are: (1) *lit-par-lit* injection of granitic magma with such fine control by former bedding planes that original structures are preserved, (2) deep burial and partial melting with present gneisses representing less refractory fractions; and (3) replacement *in situ* of original sediments by ions in dry diffusion or by hot aqueous solutions.

Chemical Data

Table 8 is a tabulation of 30 rock samples with their chemical compositions calculated

from modal analyses. Sixteen of these samples have also been chemically analyzed, and the results are listed.

Calculations of chemical compositions from the modes were made using the formulas and

(liquid) magmas as parent-materials". His argument seems to be chiefly that since nonmagmatic theories do not explain this relationship, they thereby fail as explanations for the formation of granitic bodies. It is interesting that he

TABLE 9.—ASSUMED MINERAL FORMULAS AND SPECIFIC GRAVITIES

Mineral	Sp. Gr.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O	CO_2	ZrO_2
Quartz	2.65	100.0	..	..	..	..	..	..	..	..	..	..	..	..	..
Microcline	2.55	64.7	..	18.4	..	..	..	..	..	..	16.9	..	..	..	..
Albite	2.64	68.7	..	19.5	..	..	..	..	..	11.8	..	..	..	..	..
Anorthite	2.67	43.2	..	36.7	..	..	..	..	20.1	..	..	..	..	..	..
Forsterite	3.30	42.9	..	..	..	..	..	57.1	..	..	..	..	..	..	..
Fayalite	3.30	29.4	..	..	..	70.6	..	..	..	..	..	..	..	..	..
Clinopyroxene	3.30	47.7	..	7.4	4.6	6.9	..	12.6	20.8	..	..	..	..	..	..
Orthopyroxene	3.30	51.8	..	..	..	30.9	..	17.3	..	..	..	..	..	..	..
Hornblende	3.30	37.0	..	10.5	16.4	22.0	..	8.3	5.8	..	..	..	..	..	..
Biotite	3.00	42.5	..	17.2	2.2	2.7	..	25.0	..	..	9.0	..	1.4	..	..
Sericite	2.70	45.2	..	38.5	..	..	..	..	..	..	11.8	..	4.5	..	..
Epidote and allanite	3.40	37.9	..	21.5	..	15.1	..	..	23.6	..	..	..	1.9	..	..
Ilmenite	5.00	..	52.6	..	..	47.4	..	..	..	..	..	..	..	..	..
Magnetite	5.00	..	..	..	69.0	31.0	..	..	..	..	..	..	..	..	..
Apatite	3.20	..	..	..	..	..	..	..	61.2	..	..	38.8	..	..	..
Zircon	4.70	32.8	..	..	..	..	..	..	..	..	..	..	..	..	67.2

specific gravities listed in Table 9. In general, good agreement is found between analyses and calculated compositions. The largest anomalies are in rocks which contain significant amounts of ferromagnesian minerals. Differences, as would be expected, are concentrated in elements which substitute for each other (iron, magnesium, and calcium). A comparison of the composition of the analyzed biotites and hornblendes with the assumed compositions (Table 9) shows the differences to be largely in the total FeO-Fe_2O_3 and the MgO-CaO content.

Variation Diagrams

Qu-Mi-Ab diagram.—Chayes (1952; 1954), in his investigation of calcalkaline granites of New England, used plots from modal analyses of the granites on ternary diagrams of quartz, plagioclase, and potassium feldspar as a means of summarizing and analyzing the data. Pointing out that Bowen (1937) showed that fractional crystallization of a liquid of basaltic composition would generate residual liquids lying in or near the "thermal valley", he states (1952, p. 207) "... consistent relation of data points for each mass to the thermal valley in the system Q-Or-Ab ... suggests the existence of granitic

notes in his discussion and explanation of the coincidence of data points and "thermal valley" (1952, p. 242) "... each individual granite mass shows a *curiously* systematic relation to the thermal valley" (italics by this writer).

Figure 9 is a ternary diagram quartz-albite-microcline, with the compositions of 25 rocks representing seven petrographic types plotted on it. These points bear a distinct relationship to the "thermal valley", in that the more granitic types are concentrated nearest it. The points connected by the dashed line represent the three facies of the highly contorted migmatite taken from one large specimen. It seems clear from the diagram that rocks of granitic composition will plot about the "thermal valley", regardless of their origin. The situation remains as stated by Chayes (1952, p. 243) "... we shall never be able to 'prove' that any *particular* granite is magmatic because of its composition".

Differentiation index.—Fractional crystallization of a magma will result in the residual liquid becoming enriched in alkali-alumina silicates, hence the trend of magmas changes toward a granitic composition. The sum of normative proportions of quartz, albite, orthoclase, nepheline, leucite, and kaliophilite in a rock form a convenient scale against which oxide-weight

percentages of major elements within a rock series may be plotted. This scale, known as the differentiation index (Thornton and Tuttle, 1956) has been used to classify igneous rocks and to trace crystallization trends within a magma.

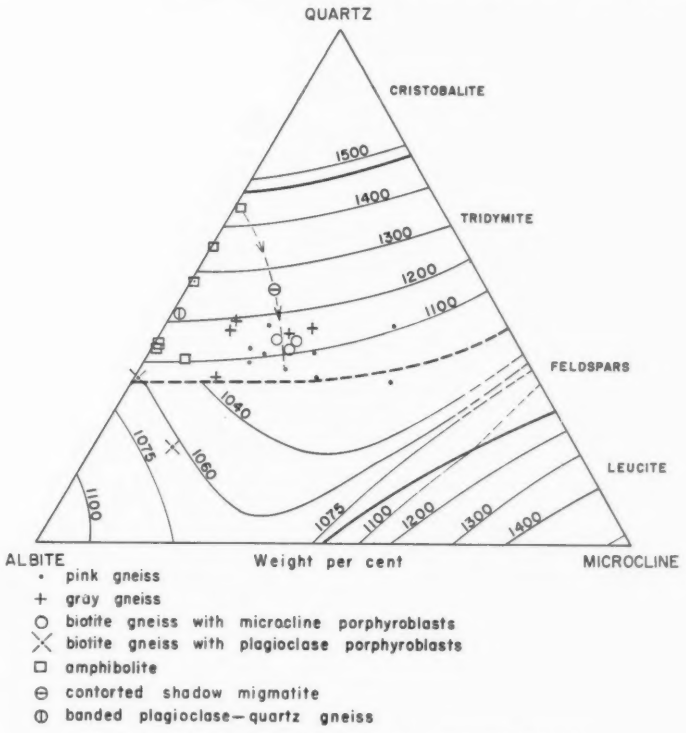


FIGURE 9.—QUARTZ-ALBITE-MICROCLINE VARIATION DIAGRAM

The differentiation indices have been determined for 25 chemically analyzed specimens and for 26 calculated rock analyses (Table 8). In Figure 10, the SiO_2, Fe_2O_3 and FeO, and MgO, Al_2O_3, CaO, Na_2O, and K_2O contents of the samples have been plotted against the differentiation index. The curves have been fitted by inspection. Although more points are needed, especially in the index range 40–70, the available points do suggest certain trends. SiO_2 increases toward the granitic end, whereas CaO correspondingly decreases. Both Al_2O_3 and Na_2O increase progressively to approximately index 75 and then drop markedly. K_2O remains nearly constant until it reaches an index of 85; then it rises abruptly. The Fe_2O_3 and FeO curve breaks markedly at about index 50; a similar break is noted with MgO, but it is not as strong.

Whether these trends are significant is not known, but they do suggest the possibility of changing chemical environment during granitization, perhaps due to temperature change, preferential fixation of ions, or changes in composition of the replacing solutions with time (Phillips, 1955, p. 8).

Theories of Origin

Granitic gneisses.—The granitic gneisses are generally well-foliated with compositional banding predominant. Exposures are excellent, especially in the cirque walls, and are commonly continuous for as much as 3000 feet along strike. Large exposures display a remarkably simple pattern of dipping planes (Pl. 1, fig. 1). The foliation, with few exceptions, is conformable with the stratification of alternating gneissic and amphibolitic horizons. Although areas were

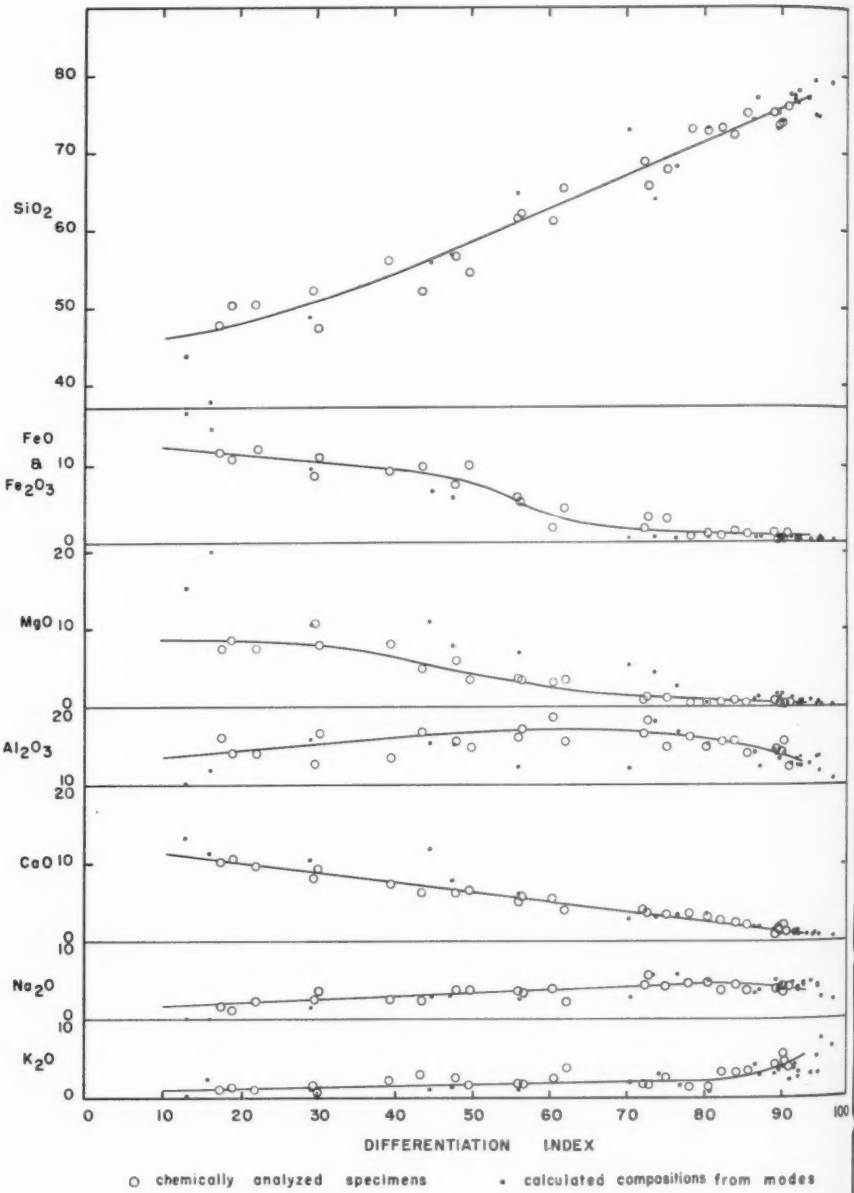


FIGURE 10.—DIFFERENTIATION-INDEX DIAGRAM

found with poor foliation or without foliation, the classical intrusive relationships of apophyses, dikes, and chilled contacts were not observed. That local flowage has taken place is demonstrated by axial-plane foliation, produced by compositional bands that were dragged into extended isoclinal folds (Pl. 2, fig. 4). A complete gradation from bedding-plane to axial-plane foliation is shown in the highly contorted migmatite of the Christmas Lake syncline.

The gray granitic gneiss is commonly associated with mafic rock types and grades into pink granitic gneiss. The biotite gneiss represents partial replacement of amphibolites. This facies is common along contacts of amphibolite with granitic gneiss and is characterized by development of feldspar porphyroblasts (Pl. 3, fig. 2) and schistosity due to alignment of biotite. The transition from massive amphibolite to biotite gneiss may take place within a few inches or several feet. Development of feldspar porphyroblasts has been observed to proceed until crystals up to 2 inches in length are formed, wrapped within biotite shells. In the Lonesome Mountain area, the series extends into lenses of orbicular rocks.

The strongest argument in favor of *lit-par-lit* injection of granite for the origin of these rocks is that examples of this process exist elsewhere and have been well described (Daly, 1915, p. 30; Allison, 1925, p. 491; Murray-Hughes, 1929, p. 117). However, the scale of the area under discussion seems to prohibit its acceptance as a major contributing mechanism. In the areas of the project where mapping has been completed, an essentially vertical plane has been examined more than 8 miles in horizontal length and 5000 feet in vertical extent, extending into the core of the Beartooth Mountains. No evidence of a parent magma exists. Since the average plunge of structures is approximately 40° S., any *lit-par-lit* introduction would have a large horizontal component. The size of the area to be so forcibly intruded, coupled with the enormous increase in volume required, would certainly result in so much deformation that the simple fold pattern would be destroyed and multiple intrusive relationships would result. A silicate melt of the type required would be characterized by a consistent chemistry and mineralogy and would contrast with the surrounding rock types. That this contrast does not exist is demonstrated by a complete series in zircon overgrowths, in An per cent of plagioclase, and in differentiation-index plots of chemical analyses. In addition, zircon studies indicate a high percentage of rounded grains with few euhedral crystals, which is not to be expected in an intrusive igneous rock. The shadow outlines of amphibolite bodies, now largely converted to granitic gneiss, prove that replacement has taken place. Thus the problem arises of the source for an intrusive magma which would have a much more siliceous composition than the observable gneisses, in order to absorb the excess Fe, Mg, and Ca and remain a leucogranitic granite.

Evidence is accumulating that rocks of granitic composition will melt within those portions of the earth's crust which are thought to be reached by geosynclinal sedimentary piles. Tuttle and Wyllie (1957) have suggested a theory by which *in situ* partial melting of a sedimentary column would produce a stratified granitic terrain. The granitic gneisses would represent the less refractory portions of the original sediments. If this had been the case, it would seem that a distinctive liquid phase would be produced at a particular pressure and temperature, and that this fluid should after crystallization be recognizable chemically and mineralogically. Such a situation would produce two distinct rock groups instead of the continuous series shown by plots of chemical analyses and listings of optical properties. Since the end product of the area's transformation is a leucogranitic gneiss, it remains difficult to explain the removal of the basified rocks after they have given up their alkalies.

Strong evidence against partial melting as an explanation for the granitic gneisses of the Beartooth block is found in the depth of burial required for melting to take place within the temperature range of 500°–600° C., indicated as the temperature during the formation of the pegmatites and gneisses. Melting of granite in this temperature range is possible only at pressures equivalent to 20 miles ($P_{H_2O} = P_{load} =$ 10,000 bars), and with high F and B (Tuttle and Wyllie, 1957). The depth appears excessive (A. F. Buddington, 1959), and the Beartooth rocks do not contain high F or B; no tourmaline or fluorite is found in heavy-liquid separation residues. Ramberg (1952, p. 244–245) argues against the production of large amounts of hydrous granitic melts within the temperatures given, and Yoder (1955, p. 506–509) cites evidence of low water content in sediments at the relatively shallow depth of 20,000 feet. These lines of evidence were reviewed by Eckelmann and Poldervaart (1957, p. 1254).

Objections to the presence of a liquid phase

have been mentioned in discussing lack of intrusive relationships. Further, the production of a fluid at great depth raises such problems as how it was kept essentially in place until it cooled. Such a body of liquid would tend to rise, destroying the simple structural patterns (Read, 1955, p. 412; Walton, 1955, p. 15).

The field evidence of continuous structures and laboratory findings of a complete transition series in rock types most strongly favor an origin by replacement *in situ*. It is known that intracrystal and intercrystal ionic diffusion occur, and that replacement does take place in this manner (Barrer, 1951). Insurmountable problems develop concerning rates of dry diffusion when applied to areas measured in tens of miles (Rankama and Sahama, 1950, p. 258; Turner and Verhoogen, 1951, p. 300; Mason, 1952, p. 215; Walton, 1955, p. 3). Even at elevated temperatures approaching 500° C., the time required by present knowledge of rates of dry diffusion is excessively long. In the area described, the amphibolite facies of metamorphism was reached before the introduction of feldspathic material (Eckelmann and Poldervaart, 1957, p. 1244). Thus most of the trapped connate water would have been dissipated and unavailable to aid migration.

Most of the problems involving rates of diffusion and transfer of heat can be solved by assumption of rising permeating aqueous solutions. Such superheated water has been produced in the laboratory by Morey and Chen (1955) within the temperature and pressure ranges that are thought to have prevailed during the granitization cycle. The solutions produced by Morey and Chen carry Na, K, Al, and Si (with slight excess of Na and K) in proportions to make granite. These solutions are also likely to produce the results found in plotting bulk chemical compositions. A continuous transition from original composition to that of a quartzofeldspathic rock would be the expected occurrence. Rocks nearly granitic in chemistry would require little addition; interstratified amphibolitic layers would take longer to be completely replaced. A remaining problem for which an answer may be proposed is the apparent addition of Na earlier than K. It might be found later that there is an affinity which favors preferential fixation of Na over K, or possibly that aqueous solutions carry a higher proportion of Na at lower temperatures.

Other rock types.—Bands of amphibolite generally conform with the structure. These bands commonly grade into granitic gneiss through the phases discussed, but in places the contact is abrupt. In these cases, the gneiss appears to invade massive amphibolite along foliation planes, filling a network of connecting joints or fractures. The over-all appearance is that of an intruding granitic magma. However, examination shows no displacement of isolated lenses of amphibolite, and field relationships indicate clearly that the rock has been replaced *in situ*, passing through the biotite gneiss stage. Studies of chemical compositions of resistant layers support field observations in metasediments to the east which indicate that the original strata were siltstones, argillites, and impure calcarenites. More highly differentiated sediments such as banded ironstone and quartzite were present in minor restricted horizons. The large amphibolitic layers examined within the Gardner Lake area are assumed to be sedimentary in origin, for they contain rounded zircons and conform to structure. However, thick orthoamphibolites are reported in the Lonesome Mountain area, and several mafic sills more than 100 feet thick were found within the metasediments of the Boulder River Plateau.

The highly contorted banded migmatite appears to be a stratigraphic unit, distinguished by thin beds and rapid alternations of rock types. This alternation of rock types has allowed the unit to behave in a more plastic manner than the surrounding, more massive bands. The result is a distinctly characteristic deformation. The difference in method of yielding is shown in Plate 3, figure 4, where thin units have deformed plastically and massive units have broken into blocks, partly replaced by transition into the biotite gneiss stage. In this instance, individual blocks have been rotated and displaced by the plastic behavior of surrounding units. The deformation of these blocks (Pl. 3, fig. 3), caused by flowage of enclosing migmatites, illustrates the relatively high viscosity. Aside from the contorted internal structures, the rocks of the Christmas Lake syncline do not differ from rocks throughout the area.

In the southeastern portion of the area, the characteristic rock type is banded plagioclase-quartz gneiss. This unit has prominent compositional foliation and small amounts of microcline, indicating that it has been relatively less granitized. The excellent compositional banding and abundant large, rounded zircons suggest a sedimentary origin for this rock unit.

Pegmatites are common throughout the area. Most are associated with well-foliated amphibolites as conformable lenses or with massive

amphibolite as crosscutting bodies which occupy joints and fractures. Field relationships indicate that the pegmatites have been formed locally, and this observation is substantiated by the high proportion of rounded zircons and similarities between the zircons in pegmatites and those in the enclosing rocks. Age determinations indicate that the pegmatites belong to the same cycle in which the granitic gneisses were formed.

Small irregular bodies of amphibolites have been described as metagabbros. These ortho-amphibolites are distinguished from para-amphibolites primarily on the basis of their structural relationships. Individual units are oval in outcrop pattern and do not exhibit the foliation characteristic of conformable amphibolite bands thought to be of sedimentary origin. Their mineralogical and chemical composition is also different from that of the para-amphibolites in that quartz is less abundant, and there is correspondingly more hornblende and a higher An content of plagioclase. The large metanorite body in the Quad Creek area has a hornblende border phase produced during granitization which is quite similar in texture to the ortho-amphibolites of the Gardner Lake area.

Geologic Chronology

Proposed Sequence of Events

Recorded geologic history began in this region with subsidence and filling of a geosynclinal basin with siltstones, argillites, impure calcarenites, and minor amounts of more highly differentiated sediments such as banded ironstone. A minimum thickness of 10,000 feet is indicated. Thick ortho-amphibolites representing flows or sills exist near by, although none have been proven within the Gardner Lake area. Deformation during or after basin subsidence produced nearly symmetrical, southward-plunging open folds. The folding was of a parallel type with little or no thickening of crest and trough. Mafic and ultramafic intrusive plugs, dikes, and sheets are intermingled with the sediments, but their exact relationship to the period of folding is not known.

Regional metamorphism of amphibolite facies came next. This evolved into granitization with the addition of alkaline ions, carried in dilute aqueous solutions passing through the rocks. Depending upon their composition and massiveness, the rocks either flowed or fractured into blocks which were rotated and deformed within the surrounding incompetent horizons. While the rocks were in the plastic state which allowed flow folding, an axial-plane foliation developed in the metasediments. This foliation was preserved as compositional banding in the granitic gneisses formed by the replacement process. Pegmatites developed at a late stage and were derived in part from the country rocks by addition of excess feldspathic material.

Three groups of mafic dikes exist in the Gardner Lake area: metapicrite, metanorite, and quartz dolerite. Metapicrite dikes occupy fractures trending east-northeast and north-northwest, whereas the metanorite set trends northeast and northwest; these two sets record two periods of tensional deformation. The quartz dolerite dikes occupy a fracture system parallel to the metanorite dikes indicating a third period of tensional deformation.

Peneplanation was the final chapter in the Precambrian history of the region; the Middle Cambrian Flathead sandstone was deposited on this surface. Slow epeirogenic subsidence existed throughout the Paleozoic and Mesozoic, with relatively more rapid depression of the Bighorn Basin suggested by thicker accumulations of sediments within the basin.

Differential uplift of the Beartooth block during the Laramide Revolution was accompanied by intrusion of felsic porphyry dikes and sills which occupied the resulting fracture systems. Thrusting completed the cycle of activity, producing the asymmetrical topographic expression of the block.

The subsequent Tertiary history includes partial overlap of the southwestern flank of the block by the Absaroka and Yellowstone volcanic rocks and continued denudation culminating in alpine glaciation which produced the present spectacular relief.

Evidence Supporting Proposed Chronology

The sedimentary origin of the rocks which make up the Beartooth block is substantiated by foliation and stratification, open and plunging folds, characteristic sedimentary lithologies such as quartzite and banded ironstone, and the high percentage of rounded zircons. Almost total absence of such minerals as staurolite, kyanite, and sillimanite in the gneisses suggests that the sediments were either poorly sorted clastic sediments, low in aluminous clays, and/or that metasomatism by aqueous solutions occurred. The presence of these minerals in the ungranitized metasediments beneath the Stillwater Complex and within the Quad Creek and

Line Creek areas indicates that the sediments were chemically weathered before being metamorphosed.

In the Lonesome Mountain area, several thick sills of ortho-amphibolite have been mapped. They are generally conformable with the folded strata. The more open and shallower folding in the Lonesome Mountain area may be due in part to these more competent bands, which would place them as pre-deformation. Small, irregular stocks and dikes of unfoliated ortho-amphibolite crosscut the stratified rocks throughout the present area. It has not been possible to date their intrusion in relationship to the folding. Orientation of pegmatites in a similar ortho-amphibolite of the Quad Creek area led Eckelmann and Poldervaart (1957, p. 1232–1233) to conclude that the intrusion was pre-folding. One small pod of ultramafic material was found within the contorted migmatite. Evidence of its pre-granitization age is clear, as it was deformed by migmatite flowage; however, correlation with the original folding is uncertain.

Large exposures of stratified beds with uniform thickness along strike plus simple relict fold structures prove that the beds were competent during the original deformation.

Since the Gardner Lake area lies within the core of the Beartooth Mountains, evidence of a prior regional metamorphism is distorted and obscured. Discordance between foliation in angular amphibolite blocks and banding in plastically deformed migmatite proves the amphibolite was formed before plastic deformation. Such blocks can be shown to form a continuous replacement series from metasediment to granitic gneiss. Feldspathized horizons in the Quad Creek area have also been traced from the core into large exposures of metasediments which have not had significant amounts of material added to them.

There is no direct evidence of the time between regional metamorphism and subsequent granitization. Locally, plastic deformation of the metamorphosed sediments occurred between the two stages, but this condition is thought to be a logical step if the transformation from "dry" to "wet" metamorphism was within one complete thermal cycle. The flow folding is in part a pregranitization feature, as it exists in all degrees of intensity in migmatites in all stages of replacement.

Pegmatites, while mostly conformable structurally, do have intrusive relationships to all rock types and thus were formed late in the process. No evidence was found of deformation in any pegmatite, although they intrude horizons which have been highly contorted. Rb-Sr and K-A age determinations on feldspars and micas from different pegmatites give identical ages, and this age is the same as that found for the biotite of the replacement gneisses. Studies show that pegmatites contain zircons identical with those found in the rock types which enclose them. The evidence is strong therefore, that the pegmatites are connected genetically with the granitization process.

Following the pegmatititic phase, tensional-fracture systems developed. One trending east-northeast and north-northwest was filled by picrite dikes. This mafic dike system has been thermally metamorphosed, as shown by clouded plagioclase and pyroxene and by coronas around olivine. The metapicrite is locally strongly magnetic, owing to the orientation of magnetite. The trend of this dike set has not been correlated with any known structural feature. An associated event may have been the beginning of the longest known period of structural control of a region by a former tectonic pattern. This pattern is that of the northeast and northwest fracture system occupied by the metanorite dikes. These dikes have trends which can be correlated with subsequent dike trends, deformation throughout the Paleozoic, and the outlines of the present block uplifted during the Laramide Revolution. The metamorphism of the metanorite is identical with that of the metapicrite. The mineralogy of the metapicrite and metanorite requires a water-deficient metamorphism and could have been produced by a second regional metamorphic cycle not recorded in the already replaced rocks, or more probably by a late water-deficient stage of the granitization cycle (Wilcox and Poldervaart, 1958).

Quartz dolerite dikes occupy a northeast-northwest fracture system parallel to the metanorites. The dolerites are generally fresh, with pigeonite and unclouded minerals. Contrast in the condition of the two rock types requires a time interval plus renewed tensional deformation between periods of intrusion. This mafic dike system is truncated by a Precambrian erosional surface upon which the Middle Cambrian Flathead sandstone is deposited.

Subsequent Paleozoic sedimentary rocks are stratified limestones, shales, and siltstones with shallow-water and terrestial features such as cross-bedding and stream-channel fillings. Contrast in thickness between sediments of the Big-horn Basin and those overlying the mountain

blocks indicates that differential movements were taking place continuously throughout the Paleozoic.

Laramide movements appear to be only an acceleration of displacement which had been taking place throughout earlier times. The present mountain front is parallel to the most prominent mafic dike trend and normal to the secondary trend. New fractures opened by the Laramide uplift have been filled by felsic porphyry dikes and sills up to 1500 feet thick, and many of the dikes have slickensided contacts showing movement after their emplacement. Porphyries also occupy echelon fractures related to the subsequent thrusting of the uplifted block. Thus, a similar age rather than an identical one is indicated for the felsic intrusive masses (Rouse *et al.*, 1937, p. 734; Eckelmann and Poldervaart, 1957, p. 1231).

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Manuscript Received by the Secretary of the Society, May 27, 1958

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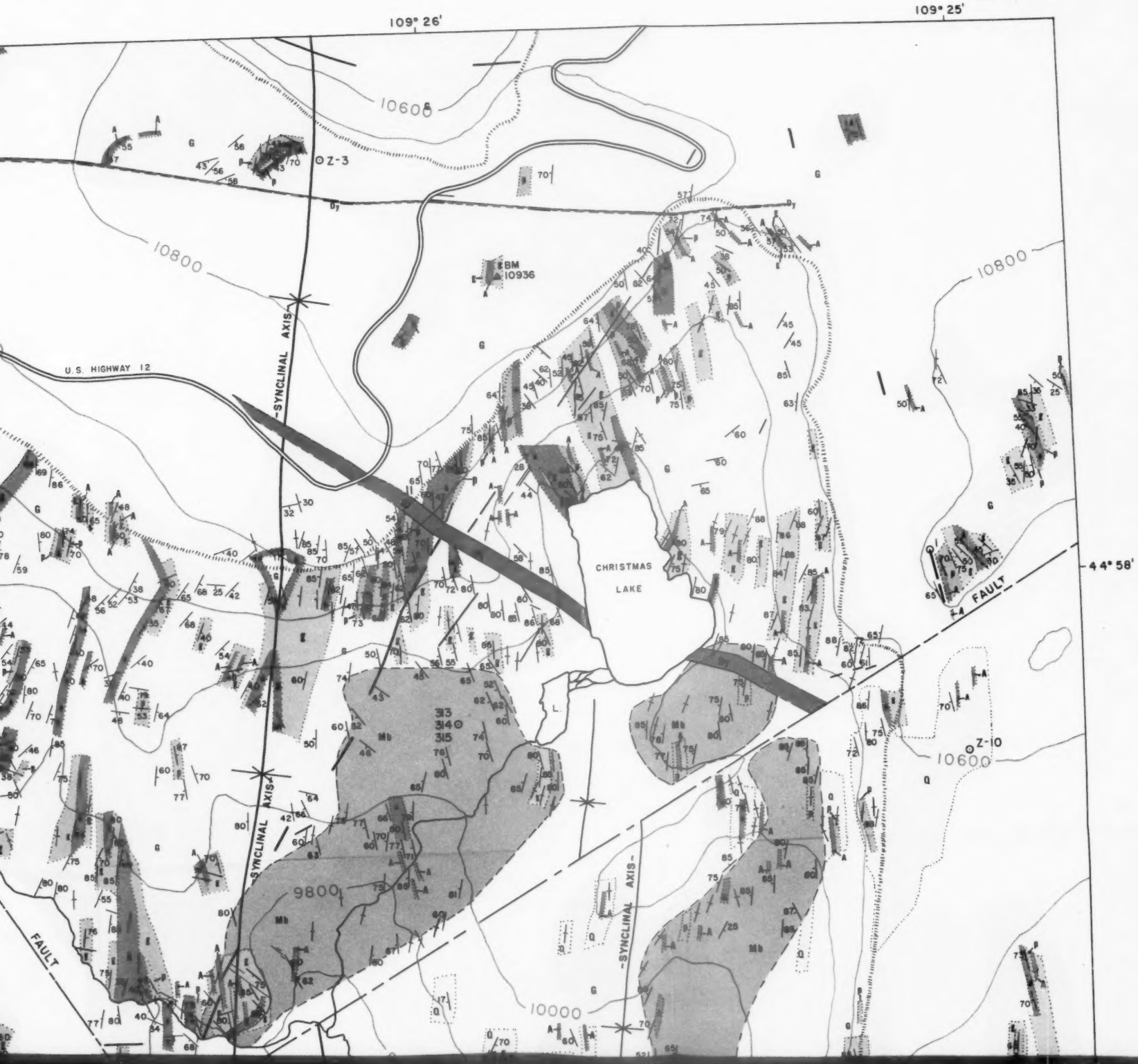
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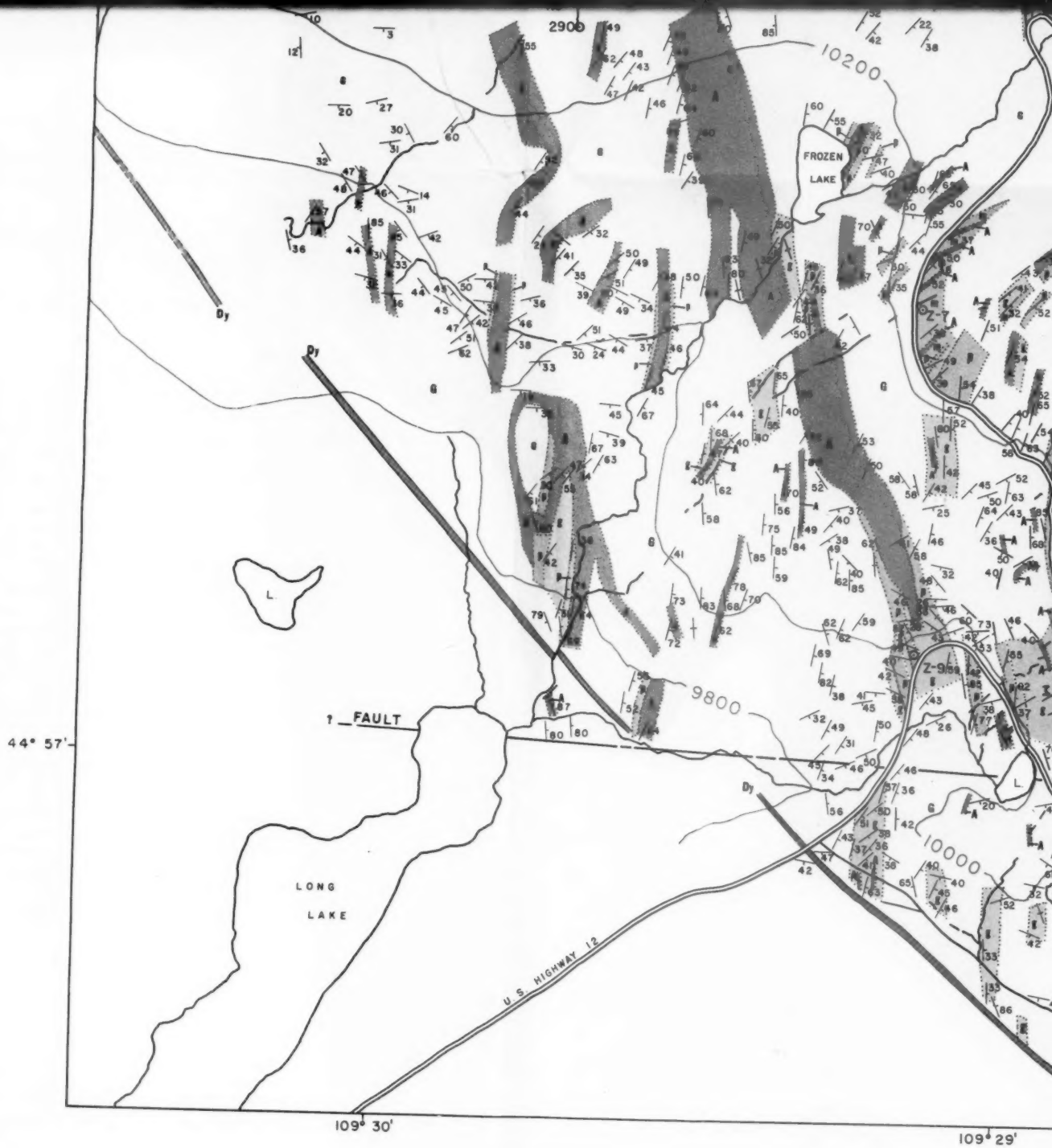
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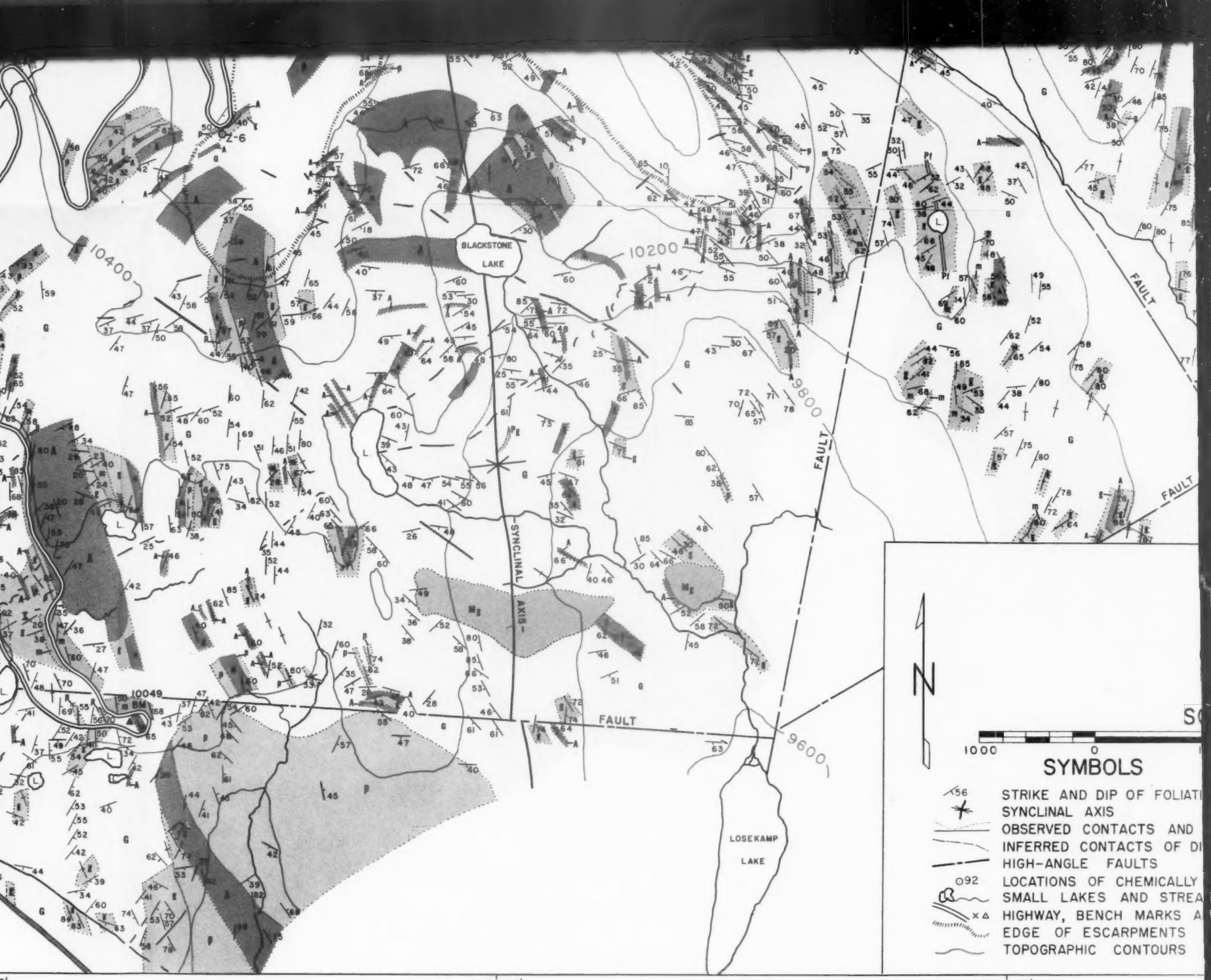

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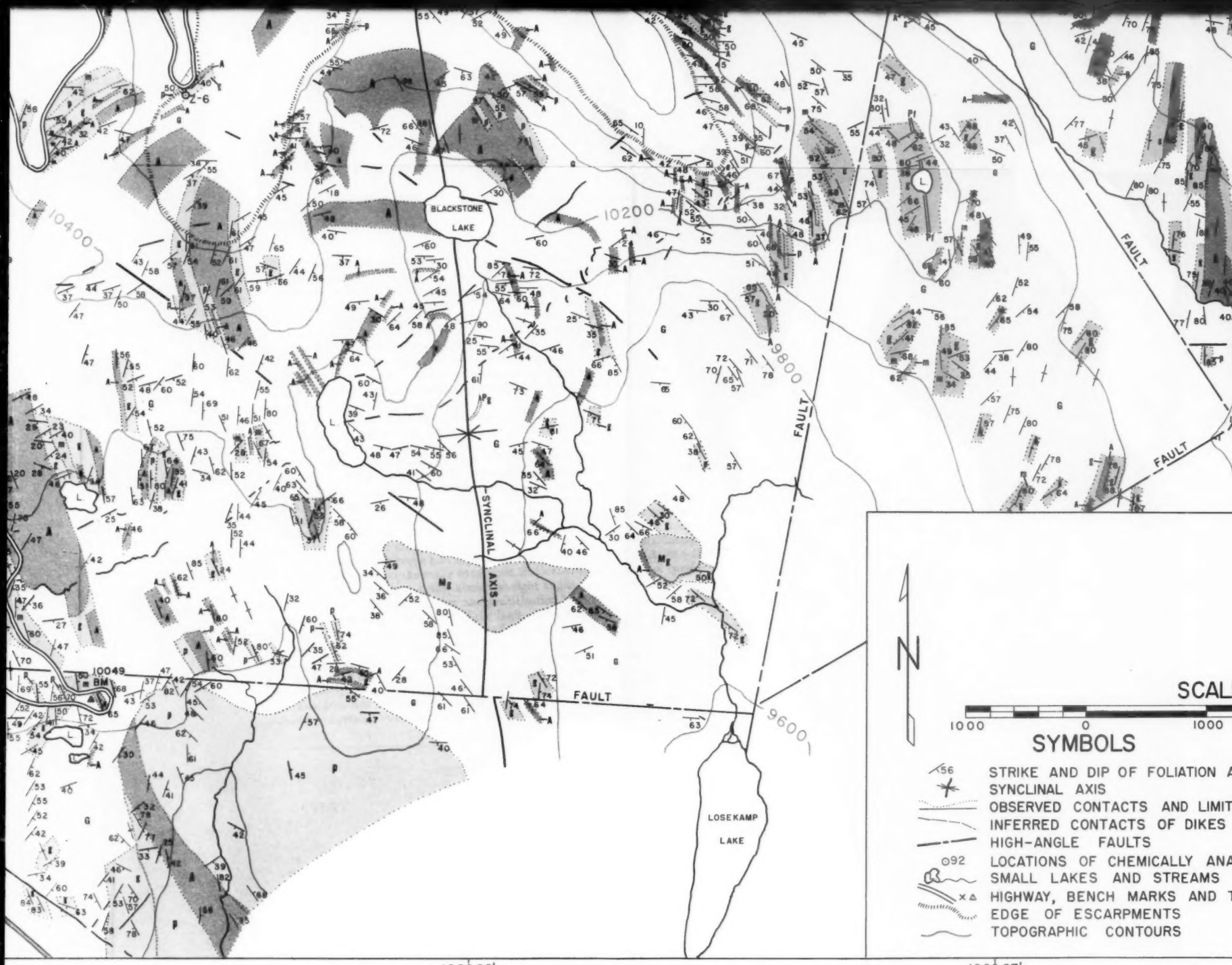

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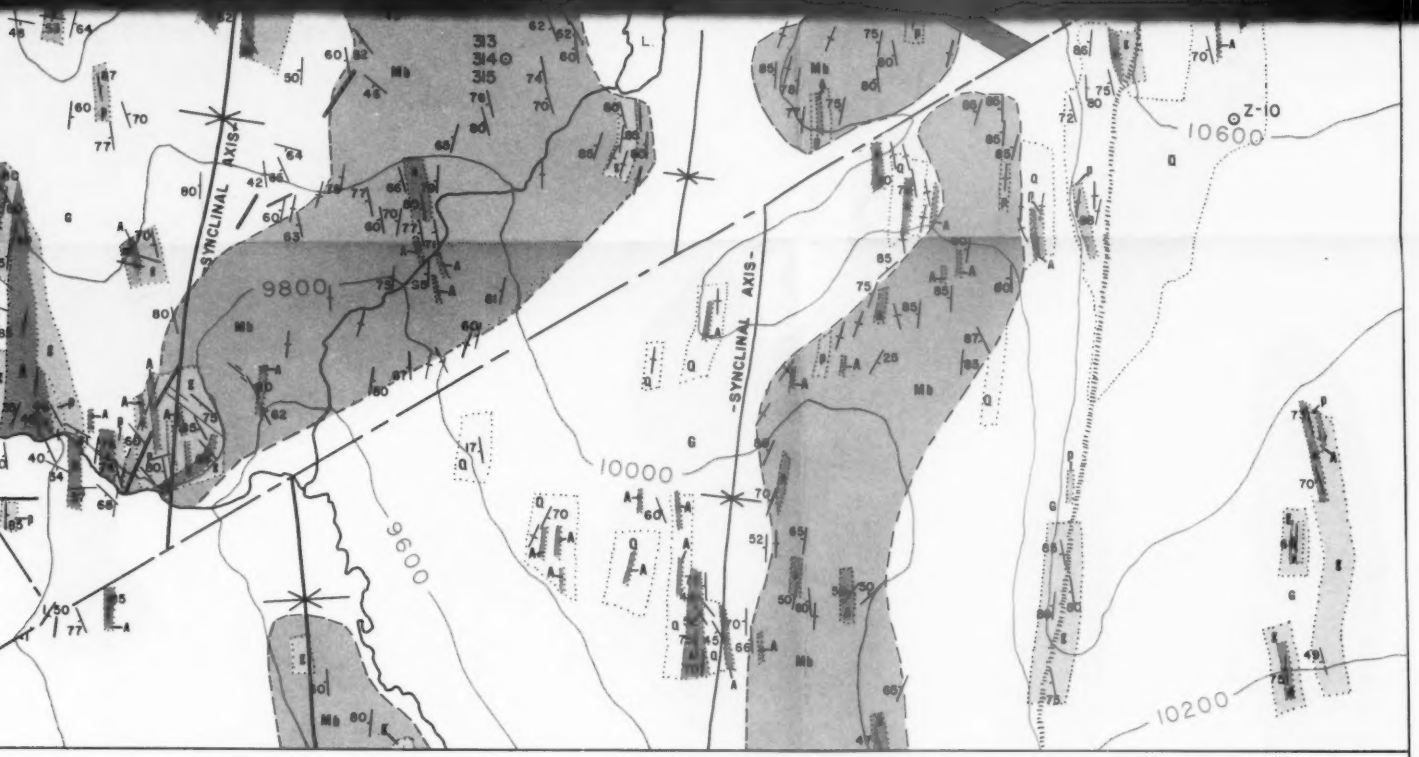

LEGEND

CRETACEOUS

- Pf — FELSIC PORPHYRY

PRECAMBRIAN

- YOUNGER PRECAMBRIAN DOLERITE DIKES
- UNDIFFERENTIATED METAPICRITE AND METANORITE DIKES
- METAGABBRO
- PEGMATITES
- G — PINK LEUCOGRANITIC GNEISS AND AREA OF NO EXPOSURE
- E — GRAY GRANITIC GNEISS
- BIOTITE GNEISS WITH PINK MICROCLINE PORPHYROBLASTS
- BIOTITE GNEISS WITH WHITE PLAGIOCLASE PORPHYROBLASTS
- Mb — HIGHLY CONTORTED BANDED MIGMATITES
- FOLIATED AMPHIBOLITE
- Q — BANDED PLAGIOCLASE - QUARTZ GNEISS

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 70, PP. 1217–1244, 18 FIGS., 4 PLS. SEPTEMBER 1959

PRECAMBRIAN ROCKS OF THE HALL VALLEY AREA, FRONT RANGE, COLORADO

BY ERNEST E. WAHLSTROM AND OK JOON KIM

ABSTRACT

The Hall Valley area, in northwestern Park County, Colorado, contains foliated high-grade Precambrian metamorphic rocks resulting from recrystallization of a complexly folded and faulted clastic sedimentary sequence containing two series of strata separated by an angular unconformity of regional extent. Some of the metamorphic rocks were further modified by migmatization and granitization, which seem to have followed an interval of extensive faulting and dislocation of the previously metamorphosed rocks. Field and laboratory data for rocks outside areas of extensive migmatization and granitization indicate the fabric, composition, and probable manner of deposition of the sedimentary layers that were present before metamorphism and provide an argument against continued use of the terms Idaho Springs formation and Swandyke gneiss for the metasedimentary rocks of the Hall Valley area.

The history of the foliated metamorphic rocks and the later migmatites and granitic rocks is interpreted as follows: (1) Deposition of a thick series of quartzose sandstones, arkoses, shales or mudstones, and limestones was terminated by uplift and gentle folding and the development of an extensive erosion surface. (2) Sedimentation resumed, and a thick, lenticular sequence of clastic quartzo-feldspathic sedimentary rocks intercalated with abundant clastic materials of probable basaltic composition was deposited over the unconformity. (3) Mafic dikes and sills were intruded into the sedimentary rocks during an interval that may have overlapped the time interval of deposition of the sedimentary rocks above the unconformity. (4) Deformation produced northwest-trending folds and was accompanied in its later stages by elevation of temperature and recrystallization of the sedimentary and igneous rocks into high-grade metamorphic rocks. (5) After a time interval of unknown duration the rocks were again dislocated along a fault of considerable displacement and northeast strike, almost at right angles to the previously formed northwest structures. (6) Migmatization and granitization later than the fault resulted from pervasive metasomatism southeast of the fault and to a lesser extent northwest of the fault. Metamorphic rocks outside the areas of migmatization show mild retrogressive changes, possibly caused by widespread penetration of solutions generated during migmatization and granitization. (7) A body of Boulder Creek granodiorite was intruded into the northeast portion of the Hall Valley area. Although the granodiorite appears to cut across the fabric of the migmatites and granitic rocks, it may be genetically related to them. (8) The area was intruded by several dikes and irregular bodies of felsic rocks that probably are related to similar rocks of Tertiary age elsewhere in the Front Range.

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INTRODUCTION

General Statement

Ball (1906, p. 371) and Spurr, Garrey, and Ball (1908, p. 37) used the term Idaho Springs formation for the Precambrian metasedimentary rocks in the vicinity of Idaho Springs, Colorado. Later investigators extended the use of the term and applied it to practically all the high-grade, foliated Precambrian metamorphic rocks of the Front Range and adjacent areas. Special suites of rocks such as the quartzites in Coal Creek Canyon, northwest of Denver, and in Big Thompson Canyon, west of Loveland, generally have not been included with the Idaho Springs formation and have been considered to be older, younger, or of the same age as the Idaho Springs formation. Lovering (1935, p. 10) in regional studies of the Front Range noted large masses of foliated rocks much richer in calcic components than the Idaho Springs formation at the type locality and proposed the term Swandyke hornblende gneiss for a series of hornblende gneisses and quartzo-feldspathic rocks well exposed in the southwestern portion of the Front Range, near Swandyke, in Summit County. He retained the term Idaho Springs formation but restricted its use to rocks resembling those near Idaho Springs.

The Idaho Springs formation at the type locality was described by Spurr, Garrey, and Ball (1908, p. 37) as follows:

"The name Idaho Springs formation is applied to a series of interbedded metamorphic crystalline rocks, presumably of sedimentary origin, which are typically exposed in the vicinity of Idaho Springs. The Idaho Springs formation includes four intensely metamorphosed crystalline members, three of which, the biotite-sillimanite schist, the biotite schist, and the quartz gneiss are interbedded with and grade into one another, while the fourth, consisting of lime-silicate rocks, although interbedded with the others, appears to grade into the quartz gneiss only."

Spurr, Garrey, and Ball observed masses of hornblende gneiss which they interpreted as metamorphosed sheets and dikes of mafic igneous rocks which cut across or were interlayered with the original sedimentary rocks.

A measure of the later extension of the use of the term Idaho Springs formation is indicated in the following description by Lovering and Goddard (1950, p. 19):

"The oldest rocks known in the Front Range are the schists and gneisses of the Idaho Springs formation, whose type locality is about 25 miles west of Denver. It consists chiefly of quartz-biotite schists and quartz-biotite-sillimanite schists, but quartzite, quartz schists, or quartz gneisses are common in some localities. A few thin lenticular beds of marble are found in the north-central part of the Front Range, and widely scattered masses of lime-silicates intergrown with garnet and magnetite suggest the metamorphism of limy beds in the central part of the range. . . . In the vicinity of Geneva Creek a few miles east of Swandyke, where one of the thickest sections of metamorphic rocks in the Front Range is exposed, the Idaho Springs formation lying below

the Swandyke gneiss has an exposed apparent thickness of about 20,000 feet, suggesting that the actual thickness is in excess of 15,000 feet."

Lovering (1935, p. 10) described the Swandyke hornblende gneiss as "hornblendic gneisses and schists with some interlayered quartz schists, all intimately injected by pegmatite, aplite, granite, and granite gneiss." Lovering and Goddard (1950, p. 20) later interpreted the Swandyke gneiss as the product of metamorphism of quartz diorite flows or sills interbedded with clastic sedimentary rocks and suggested that the rocks were in part contemporaneous with and in part younger than the Idaho Springs formation and wrote that

"... the gneiss locally is very calcic and grades into lenses of coarse calcite. Thin beds of quartzite and quartz-biotite schist are common in the calcic zones, and in a few place magnetite jaspilite is present. It is believed that these variants represent thin clastic and hot-springs deposits interlayered with dominantly volcanic material."

Lovering and Goddard estimated that the thickness of the Swandyke gneiss at the type locality is approximately 6000 feet.

The Idaho Springs formation is not a formation in the ordinary sense. As generally used, the term refers to a laterally extensive assemblage of foliated rocks of complex but fairly distinctive lithology and fabric formed by the high-grade regional metamorphism of a thick sequence of clastic, relatively noncalcareous sedimentary rocks. Similarly, the Swandyke hornblende gneiss is the result of the metamorphism of a succession of interlayered calcareous and quartzo-feldspathic sedimentary rocks and is exemplified by the extensive hornblendic schists and gneisses interlayered with quartzo-feldspathic gneisses in the southwestern portion of the Front Range. There is no basis for the assumption that rocks that have been classified as Idaho Springs formation or Swandyke hornblende gneiss in one part of the Front Range were metamorphosed at the same time or involved original materials of the same geologic age as rocks similarly classified in other portions of the Front Range. The Precambrian core of the Front Range has had a complicated history, and indiscriminate classification of the foliated metamorphic rocks into two or three general categories does not serve a useful purpose in the interpretation of the geologic history. However, metasedimentary rocks that have fabrics and mineralogy similar to those in the rock assemblages near Idaho Springs can be classified as the Idaho Springs type of metasedimentary rock; metamorphosed rocks similar to those near Swandyke can be referred to as the Swandyke type of rock.

Much of the geologic history recorded in the Idaho Springs and Swandyke types of metamorphic rocks in the Front Range has been obliterated by masses of granitic rocks of batholithic dimensions and by extensive bodies of migmatite in which original fabrics and mineral associations have been greatly modified or destroyed. In some areas relict fabrics and stratigraphic sequences are fairly well preserved and yield the kind of data that ultimately may permit interpretation of the details of the geologic history of the very old and structurally complex rocks exposed in the core of the Front Range. The Hall Valley area in the southwestern portion of the Front Range (Fig. 1) is such an area and contains a variety of Precambrian rocks, including rocks of the Idaho Springs and Swandyke types, migmatites, and granitic rocks. The area is near the type locality for the Swandyke gneiss, and exposures are extensive enough to permit determination of the relationships between the Idaho Springs and Swandyke types of rocks and adequate analyses of fabrics and mineral associations in all the rocks.

Methods of Investigation and Acknowledgments

Field mapping of the Hall Valley area was done during the summer months of 1952 and 1953 using aerial photographs. Data on the photographs were adjusted photogrammetrically and then transferred to base maps enlarged from United States Geological Survey topographic maps of the Como and Montezuma quadrangles. Laboratory work was completed during the years 1952 through 1954 at the University of Colorado. Field and laboratory investigations were made by Kim with the collaboration of Wahlstrom. The manuscript and illustrations were prepared by Wahlstrom and are a condensation and revision of a thesis presented by Kim to the University of Colorado in partial fulfillment of the requirements for the Ph.D. degree.

The writers are grateful for the assistance given by colleagues and associates, especially L. A. Warner and W. A. Braddock, who read the manuscript and offered helpful suggestions. P. K. Sims of the United States Geological Survey reviewed the original manuscript and

made many helpful critical comments. Financial assistance from the State Department of the United States contributed to the support of Kim's part of the study.

made here to establish formation names; instead, the various recognizable lithologic assemblages are identified merely as units. At some future date additional regional studies probably

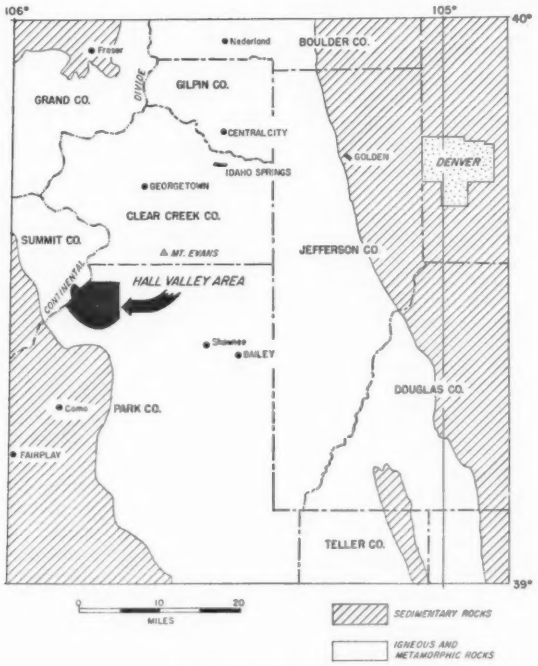


FIGURE 1.—INDEX MAP
Location of the Hall Valley area

NOMENCLATURE AND AGE RELATIONSHIPS OF THE PRECAMBRIAN METASEDIMENTARY ROCKS

In the present study the terms Idaho Springs formation and Swandyke gneiss have been abandoned in favor of letter designations. An unconformity in the northwest portion of the Hall Valley area (Pl. 4), here designated as the Hall Valley unconformity, represents a major interruption in the deposition of the sedimentary rocks that later were subjected to metamorphism. The succession of layered metasedimentary rocks below the unconformity is designated as the *A* series, and the succession above the unconformity is identified as the *B* series (Pl. 1). Each of several thick, distinctive units within each of the series, would merit designation as a formation in an unmetamorphosed sedimentary section. No attempt is

will justify major and minor stratigraphic subdivisions and correlations, and, possibly, establishment of an appropriate nomenclature not only for Hall Valley but for other portions of the Front Range.

The rocks in the *A* series are predominantly the Idaho Springs type of metasedimentary rock, but at least three thick, persistent lime-silicate units contain abundant hornblende and calcic plagioclase and resemble some of the hornblendic Swandyke type of rock. The *B* series, above the unconformity, contains abundant rocks of the Swandyke type and, in addition, numerous thick and thin layers of micaceous quartzo-feldspathic rocks of the Idaho Springs type. The intercalation of calcic and noncalcic layers in both series probably is the basis for the statement by Lovering and Goddard (1950, p. 20) that the Swandyke gneiss

is in part contemporaneous with and in part later than the Idaho Springs formation.

The upper limits of the *B* series and the lower limits of the *A* series could not be determined in the Hall Valley area. The maximum thickness of the *A* series as measured downward from the unconformity to a level where granitization and migmatization have obscured the original relationships is approximately 10,000 feet, a substantial fraction of the estimate by Lovering and Goddard (1950, p. 20) of 15,000 feet for the Idaho Springs formation in the vicinity of Geneva Creek. Similarly, an estimated thickness of the *B* series, as measured from the unconformity upward to the highest exposed units in the Hall Valley area, is approximately 5900 feet, compared with Lovering and Goddard's (1950, p. 20) estimate of 6000 feet for the Swandyke gneiss at the type locality.

The angular unconformity between the *A* series and the *B* series strikes approximately N. 15°W., and the angular discordance between the layered rocks dipping steeply to the southwest above and below the unconformity is 5°–15°. Rocks in the *B* series above the unconformity are lenticular and probably formed initially by the accumulation of coarse clastic rocks after erosion and weathering of the tilted underlying rocks. Exposures of the unconformity are generally poor. Rocks in a bleached zone lying beneath and parallel to the unconformity grade downward into darker, more conspicuously foliated rocks. This zone has a maximum thickness of about 50 feet and contains numerous bodies of aplite and pegmatite which appear to have formed locally by metasomatism and partial to complete mobilization of quartzo-feldspathic rocks. The zone intersects the layering of the rocks below the unconformity and is in a position indicating that it is a metamorphosed regolith.

The possibilities that the apparently unconformable relationship between the *A* and *B* series could be explained by faulting and that the bleached zone below the unconformity could be the result of hydrothermal alteration were considered early in the investigation. The few exposures of the unconformity in the field, and particularly an exposure in a cirque at the head of Hall Valley, show no indication of fault movement along the surface of contact between the *A* and *B* series. Comparison of the rocks below the unconformity with hydrothermally bleached rocks containing abundant sericite and pyrite from Red Cone Peak and other localities in the Hall Valley area indicates that the medium- to coarse-grained, relatively fresh, light-colored rocks below the unconformity were deficient in dark components before metamorphism and that subsequent alteration, hydrothermal or otherwise, is not the cause of the bleaching.

Subdivision and Description of the *A* and *B* Series

Description

The normal sequence of layers in the *A* and *B* series is most easily determined where granitic rocks and migmatites are absent or present only in small amounts. In the Hall Valley area these conditions are fulfilled in the northwest portion of the area in glaciated valleys east and south of the Continental Divide (Pl. 4). Granitization and migmatization in the south and east portions of the area have so profoundly modified the original rocks that all attempts to recognize and map distinctive units in orderly sequence were unsuccessful.

Field recognition of the various units in the *A* series is expedited by determining the position of each unit relative to one or more of three conspicuous and laterally extensive lime-silicate layers. Each of the other units, except those consisting dominantly of quartz-biotite gneiss, possesses distinctive fabrics and mineralogy. Subdivision and brief descriptions of the units in both the *A* series and *B* series are included in the Appendix.

Mineralogy

Complex intercalation of a variety of distinct and gradational rock types in every unit of both the *A* and *B* series prevents detailed description of the quantitative mineralogy of each unit. Brief, generalized descriptions are given for the volumetrically important minerals constituting the entire sequence outside the areas of migmatization and granitization. Reference is made to mineralogical changes that seem to be associated with migmatization and granitization but have not resulted in gross changes in the original metamorphic mineral assemblages.

QUARTZ: Two kinds of quartz grains are present. Small, round grains 0.05–0.2 mm in diameter commonly are enclosed by larger grains of mica or feldspar and have brownish or grayish rims. Petrofabric analysis and general

appearance indicate that the small grains are relict clastic components and have been protected from deformation and recrystallization by the enclosing minerals. Much more abundant are larger quartz grains 0.2–3.0 mm in diameter forming single anhedral crystals and aggregates. The larger quartz grains show a variety of shapes. In mica-rich rocks the grains are commonly equant, whether in single crystals or aggregates. In brittle rocks such as quartzite all gradations are seen between equant strained grains and crushed single crystals or aggregates which have been dragged out into lenses or streaks interlayered with other minerals, especially mica and sillimanite. Recrystallization of quartz grains of a variety of shapes but especially the crushed or deformed quartz has produced essentially unstrained crystals or aggregates which have long dimensions parallel to the foliation.

Near bodies of migmatite and granitic rocks quartz replaces plagioclase in myrmekite, forms a sieve fabric with hornblende, and is present in graphic intergrowths with potassium feldspar, in addition to occurring in larger single grains and clusters.

MICROCLINE AND ORTHOCLASE: Microcline is abundant in the quartzose rocks and in smaller amounts in nonquartzose rocks and appears to have formed at the expense of original potassic components of the rock or, locally, by introduction from an outside source. The minerals appear in grains 0.2–0.5 mm in length. Many of the larger grains contain inclusions of plagioclase, quartz, or biotite.

Some grains of potassium feldspar show cores or irregular patches of untwinned potassium feldspar surrounded by or in gradational contact with twinned microcline. The untwinned feldspar (orthoclase) probably represents a stable phase at the maximum temperatures attained during metamorphism, and the microcline in such associations probably formed by inversion. Where twinned microcline occurs by itself it could not be ascertained whether it is an inversion product or the result of direct crystallization as a stable phase.

PLAGIOCLASE: Plagioclase is an abundant component of many units of both the *A* series and the *B* series, especially in the calcareous units of both series. In the quartzose and micaceous rocks some grains are bent and shattered and are twinned or untwinned. In many bent grains twinning has been induced by stress. In micaceous rocks the composition of the plagioclase in larger grains is commonly oligoclase or andesine, but smaller grains and veinlets are albite or sodic oligoclase. Plagioclase in contact with microcline commonly shows albitic rims and tends to be more altered and cloudy than grains in contact with other minerals.

In the calcareous layers of the *B* series and in the lime-silicate units of the *A* series calcic plagioclases (calcic andesine, labradorite, or bytownite) predominate and are in close association with pyroxene and/or hornblende.

Poikilitic inclusions are abundant in some grains of plagioclase, especially those in micaceous and quartzose rocks.

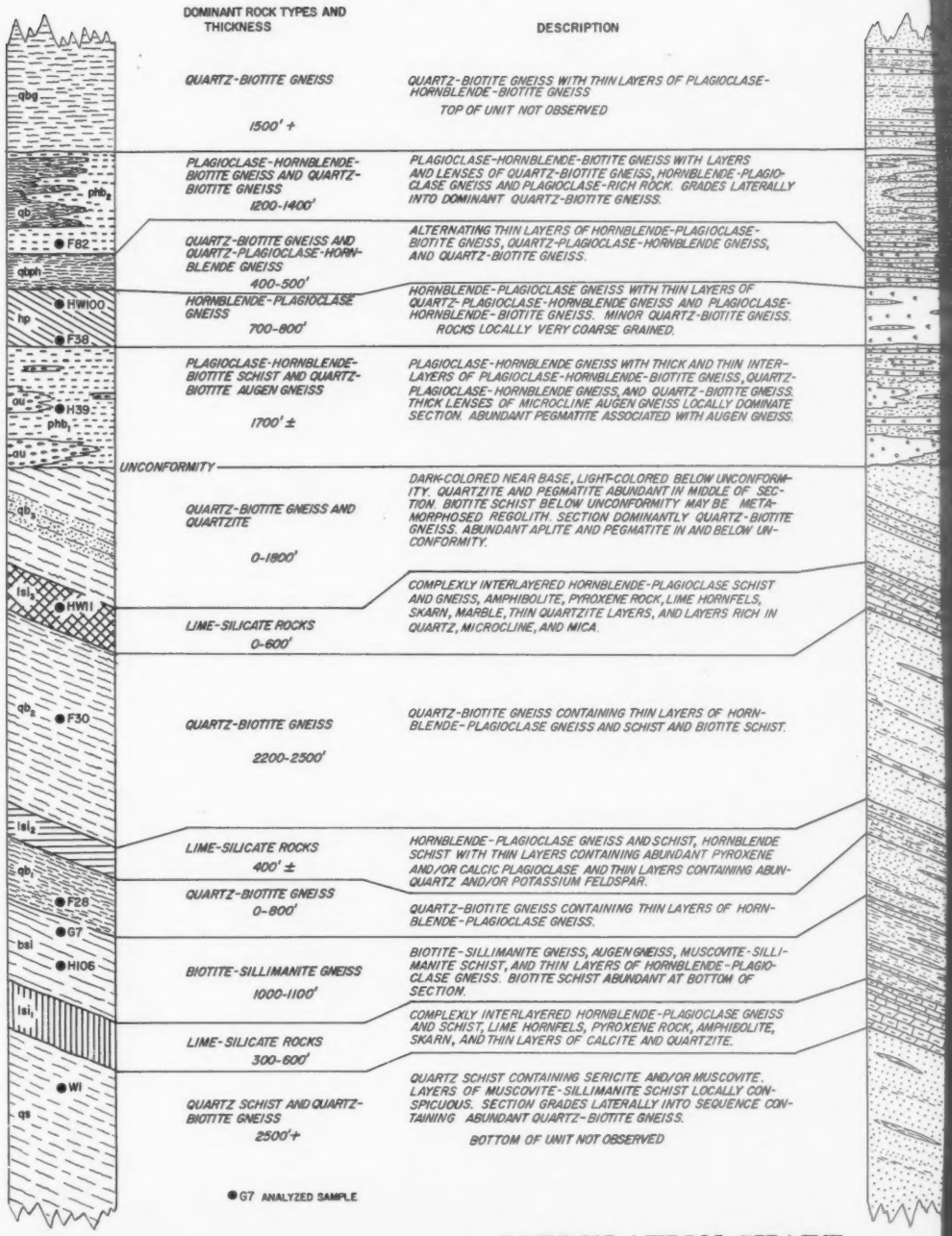
PYROXENE: The largest concentrations of pyroxene are in massive-granular pyroxene rocks and in interlayers of pyroxene and hornblende in the lime-silicate units of the *A* series. Small amounts are present in calcareous layers in the *B* series and as porphyroblasts in some of the quartzites. Most of the pyroxene is diopside and is colorless in thin section, but in several layers in the lime-silicate rocks greenish augite predominates. Whether the pyroxene is diopside or augite seems to be determined by original differences in the compositions of the parent rocks.

Partial to complete alteration of the pyroxene to bluish-green hornblende is seen in all pyroxene-bearing rocks and suggests that the pyroxene represents maximum metamorphic intensity and that the hornblende formed later in a milder environment, or that the pyroxene was recrystallized in a "dry" environment and was subsequently converted to hornblende as a result of introduction of water and mafic components, with or without a change in temperature (Yoder, 1955, p. 519). Uralitization of the pyroxene may have accompanied granitization and migmatization of rocks in adjacent areas.

BIOTITE: Two types of biotite are present in the quartzo-feldspathic rocks. The more abundant type forms sharply defined brownish plates essentially parallel to the foliation of the enclosing rocks. The second type appears in bent and frayed turbid plates or shreds in sheared aggregates or bent around grains of quartz and feldspar. The turbid variety increases in amount in the direction of the migmatites and is later than the clear biotite.

MUSCOVITE AND SERICITE: Muscovite is present in plates oblique to the schistosity, in parallel intergrowths with biotite, and in sericite aggregates formed by the alteration of sillimanite. In some sericite aggregates muscovite formed by recrystallization of sericite, and in

PRECAMBRIAN METASEDIMENTARY ROCKS
(EXCLUDING GRANITIZED AND MIGMATIZED ROCKS)


DOMINANT ROCK TYPES AND THICKNESS
DESCRIPTION
B SERIES
A SERIES
qbg
QUARTZ-BIOTITE GNEISS
1500' +
QUARTZ-BIOTITE GNEISS WITH THIN LAYERS OF PLAGIOCLASE-HORNBLENDE-BIOTITE GNEISS
TOP OF UNIT NOT OBSERVED
phb2
qb
PLAGIOCLASE-HORNBLENDE-BIOTITE GNEISS AND QUARTZ-BIOTITE GNEISS
1200-1400'
PLAGIOCLASE-HORNBLENDE-BIOTITE GNEISS WITH LAYERS AND LENSES OF QUARTZ-BIOTITE GNEISS, HORNBLENDE-PLAGIOCLASE GNEISS AND PLAGIOCLASE-RICH ROCK. GRADES LATERALLY INTO DOMINANT QUARTZ-BIOTITE GNEISS.
F82
qbph
QUARTZ-BIOTITE GNEISS AND QUARTZ-PLAGIOCLASE-HORNBLENDE GNEISS
400-500'
ALTERNATING THIN LAYERS OF HORNBLENDE-PLAGIOCLASE-BIOTITE GNEISS, QUARTZ-PLAGIOCLASE-HORNBLENDE GNEISS, AND QUARTZ-BIOTITE GNEISS.
HWI00
hp
HORNBLENDE-PLAGIOCLASE GNEISS
700-800'
HORNBLENDE-PLAGIOCLASE GNEISS WITH THIN LAYERS OF QUARTZ-PLAGIOCLASE-HORNBLENDE GNEISS AND PLAGIOCLASE-HORNBLENDE-BIOTITE GNEISS. MINOR QUARTZ-BIOTITE GNEISS. ROCKS LOCALLY VERY COARSE GRAINED.
F38
au
H39
phb1
PLAGIOCLASE-HORNBLENDE-BIOTITE SCHIST AND QUARTZ-BIOTITE AUGEN GNEISS
1700' ±
PLAGIOCLASE-HORNBLENDE GNEISS WITH THICK AND THIN INTERLAYERS OF PLAGIOCLASE-HORNBLENDE-BIOTITE GNEISS, QUARTZ-PLAGIOCLASE-HORNBLENDE GNEISS, AND QUARTZ-BIOTITE GNEISS. THICK LENSES OF MICROCLINE AUGEN GNEISS LOCALLY DOMINATE SECTION. ABUNDANT PEGMATITE ASSOCIATED WITH AUGEN GNEISS.
UNCONFORMITY
DARK-COLORED NEAR BASE, LIGHT-COLORED BELOW UNCONFORMITY. QUARTZITE AND PEGMATITE ABUNDANT IN MIDDLE OF SECTION. BIOTITE SCHIST BELOW UNCONFORMITY MAY BE METAMORPHOSED REGOLITH. SECTION DOMINANTLY QUARTZ-BIOTITE GNEISS. ABUNDANT APLITE AND PEGMATITE IN AND BELOW UNCONFORMITY.
qb3
QUARTZ-BIOTITE GNEISS AND QUARTZITE
0-1800'
lsi3
HWII
COMPLEXLY INTERLAYERED HORNBLENDE-PLAGIOCLASE SCHIST AND GNEISS, AMPHIBOLITE, PYROXENE ROCK, LIME HORNFELS, SKARN, MARBLE, THIN QUARTZITE LAYERS, AND LAYERS RICH IN QUARTZ, MICROCLINE, AND MICA.
LIME-SILICATE ROCKS
0-600'
qb2
F30
QUARTZ-BIOTITE GNEISS
2200-2500'
QUARTZ-BIOTITE GNEISS CONTAINING THIN LAYERS OF HORNBLENDE-PLAGIOCLASE GNEISS AND SCHIST AND BIOTITE SCHIST.
lsi2
LIME-SILICATE ROCKS
400' ±
HORNBLENDE-PLAGIOCLASE GNEISS AND SCHIST, HORNBLENDE SCHIST WITH THIN LAYERS CONTAINING ABUNDANT PYROXENE AND/OR CALCIC PLAGIOCLASE AND THIN LAYERS CONTAINING ABUNDANT QUARTZ AND/OR POTASSIUM FELDSPAR.
qb1
F28
QUARTZ-BIOTITE GNEISS
0-800'
QUARTZ-BIOTITE GNEISS CONTAINING THIN LAYERS OF HORNBLENDE-PLAGIOCLASE GNEISS.
G7
bsi
HI06
BIOTITE-SILLIMANITE GNEISS
1000-1100'
BIOTITE-SILLIMANITE GNEISS, AUGEN GNEISS, MUSCOVITE-SILLIMANITE SCHIST, AND THIN LAYERS OF HORNBLENDE-PLAGIOCLASE GNEISS. BIOTITE SCHIST ABUNDANT AT BOTTOM OF SECTION.
lsi1
COMPLEXLY INTERLAYERED HORNBLENDE-PLAGIOCLASE GNEISS AND SCHIST, LIME HORNFELS, PYROXENE ROCK, AMPHIBOLITE, SKARN, AND THIN LAYERS OF CALCITE AND QUARTZITE.
LIME-SILICATE ROCKS
300-600'
WI
qs
QUARTZ SCHIST AND QUARTZ-BIOTITE GNEISS
2500'+
QUARTZ SCHIST CONTAINING SERICITE AND/OR MUSCOVITE. LAYERS OF MUSCOVITE-SILLIMANITE SCHIST LOCALLY CONSPICUOUS. SECTION GRADES LATERALLY INTO SEQUENCE CONTAINING ABUNDANT QUARTZ-BIOTITE GNEISS.
BOTTOM OF UNIT NOT OBSERVED
● G7 ANALYZED SAMPLE

CORRELATION CHART

Shows metamorphic rocks of Hall Valley area, Front Range, Colorado, and probab

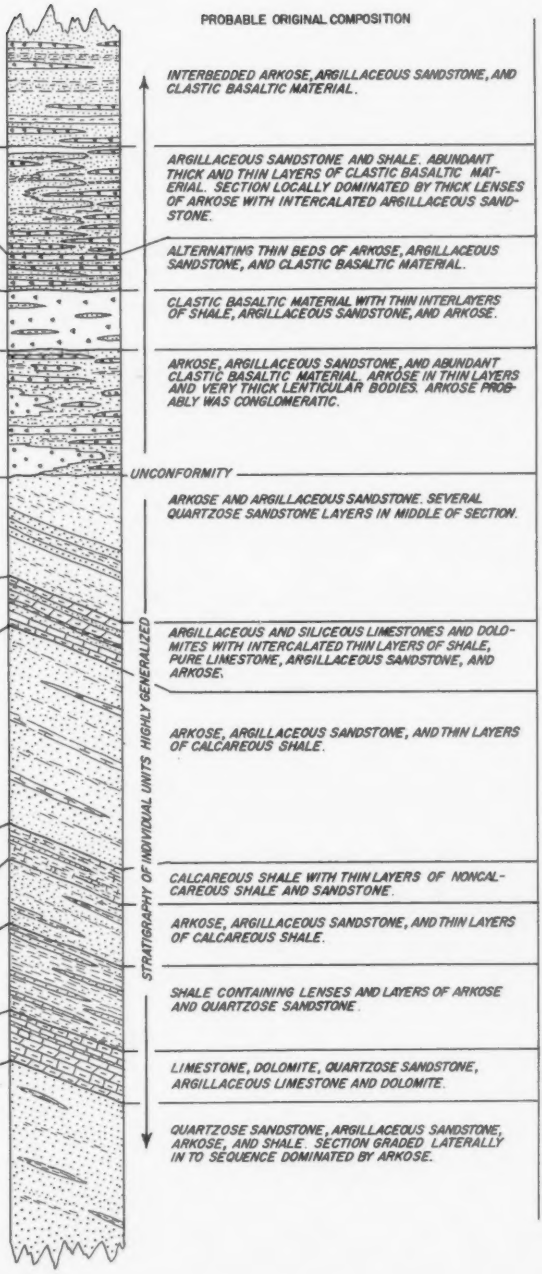
PRECAMBRIAN METASEDIMENTARY ROCKS
EXCLUDING GRANITIZED AND MIGMATIZED ROCKS)

AND	DESCRIPTION
S	QUARTZ-BIOTITE GNEISS WITH THIN LAYERS OF PLAGIOCLASE-HORNBLENDE-BIOTITE GNEISS TOP OF UNIT NOT OBSERVED
NDE-RTZ-	PLAGIOCLASE-HORNBLENDE-BIOTITE GNEISS WITH LAYERS AND LENSES OF QUARTZ-BIOTITE GNEISS, HORNBLENDE-PLAGI CLASE GNEISS AND PLAGIOCLASE-RICH ROCK. GRADES LATERAL INTO DOMINANT QUARTZ-BIOTITE GNEISS.
AND HORN-	ALTERNATING THIN LAYERS OF HORNBLENDE-PLAGIOCLASE-BIOTITE GNEISS, QUARTZ-PLAGIOCLASE-HORNBLENDE GNEISS, AND QUARTZ-BIOTITE GNEISS.
LASE	HORNBLENDE-PLAGIOCLASE GNEISS WITH THIN LAYERS OF QUARTZ-PLAGIOCLASE-HORNBLENDE GNEISS AND PLAGIOCLAS HORNBLENDE-BIOTITE GNEISS. MINOR QUARTZ-BIOTITE GNEI ROCKS LOCALLY VERY COARSE GRAINED.
NDE-RTZ-	PLAGIOCLASE-HORNBLENDE GNEISS WITH THICK AND THIN INTE LAYERS OF PLAGIOCLASE-HORNBLENDE-BIOTITE GNEISS, QUAR PLAGIOCLASE-HORNBLENDE GNEISS, AND QUARTZ-BIOTITE GNE THICK LENSES OF MICROCLINE AUGEN GNEISS LOCALLY DOMINA SECTION. ABUNDANT PEGMATITE ASSOCIATED WITH AUGEN GNE
AND	DARK-COLORED NEAR BASE, LIGHT-COLORED BELOW UNCONFOR ITY. QUARTZITE AND PEGMATITE ABUNDANT IN MIDDLE OF SE TION. BIOTITE SCHIST BELOW UNCONFORMITY MAY BE META-MORPHOSED REGOLITH. SECTION DOMINANTLY QUARTZ-BIOT GNEISS. ABUNDANT APLITE AND PEGMATITE IN AND BELOW UN-CONFORMITY.
	COMPLEXLY INTERLAYERED HORNBLENDE-PLAGIOCLASE SCHIST AND GNEISS, AMPHIBOLITE, PYROXENE ROCK, LIME HORNFELS, SKARN, MARBLE, THIN QUARTZITE LAYERS, AND LAYERS RICH IN QUARTZ, MICROCLINE, AND MICA.
	QUARTZ-BIOTITE GNEISS CONTAINING THIN LAYERS OF HORN-BLENDE-PLAGIOCLASE GNEISS AND SCHIST AND BIOTITE SCHI
	HORNBLENDE-PLAGIOCLASE GNEISS AND SCHIST, HORNBLEND SCHIST WITH THIN LAYERS CONTAINING ABUNDANT PYROXENE AND/OR CALCIC PLAGIOCLASE AND THIN LAYERS CONTAINING AB QUARTZ AND/OR POTASSIUM FELDSPAR.
	QUARTZ-BIOTITE GNEISS CONTAINING THIN LAYERS OF HORN-BLENDE-PLAGIOCLASE GNEISS.
EISS	BIOTITE-SILLIMANITE GNEISS, AUGEN GNEISS, MUSCOVITE-SILL MANITE SCHIST, AND THIN LAYERS OF HORNBLENDE-PLAGIO CLASE GNEISS. BIOTITE SCHIST ABUNDANT AT BOTTOM OF SECTION.
	COMPLEXLY INTERLAYERED HORNBLENDE-PLAGIOCLASE GNEIS AND SCHIST, LIME HORNFELS, PYROXENE ROCK, AMPHIBOLITE, SKARN, AND THIN LAYERS OF CALCITE AND QUARTZITE.
RTZ-	QUARTZ SCHIST CONTAINING SERICITE AND/OR MUSCOVITE. LAYERS OF MUSCOVITE-SILLIMANITE SCHIST LOCALLY CON SPICUOUS. SECTION GRADES LATERALLY INTO SEQUENCE C TAINING ABUNDANT QUARTZ-BIOTITE GNEISS. BOTTOM OF UNIT NOT OBSERVED
PLE	

CORRELATION CH

rocks of Hall Valley area, Front Range, Colo

ORIGINAL SEDIMENTARY ROCKS


PROBABLE ORIGINAL COMPOSITION
INTERBEDDED ARKOSE, ARGILLACEOUS SANDSTONE, AND CLASTIC BASALTIC MATERIAL.
ARGILLACEOUS SANDSTONE AND SHALE. ABUNDANT THICK AND THIN LAYERS OF CLASTIC BASALTIC MATERIAL. SECTION LOCALLY DOMINATED BY THICK LENSES OF ARKOSE WITH INTERCALATED ARGILLACEOUS SANDSTONE.
ALTERNATING THIN BEDS OF ARKOSE, ARGILLACEOUS SANDSTONE, AND CLASTIC BASALTIC MATERIAL.
CLASTIC BASALTIC MATERIAL WITH THIN INTERLAYERS OF SHALE, ARGILLACEOUS SANDSTONE, AND ARKOSE.
ARKOSE, ARGILLACEOUS SANDSTONE, AND ABUNDANT CLASTIC BASALTIC MATERIAL. ARKOSE IN THIN LAYERS AND VERY THICK LENTICULAR BODIES. ARKOSE PROBABLY WAS CONGLOMERATIC.
UNCONFORMITY
ARKOSE AND ARGILLACEOUS SANDSTONE. SEVERAL QUARTZOSE SANDSTONE LAYERS IN MIDDLE OF SECTION.
ARGILLACEOUS AND SILICEOUS LIMESTONES AND DOLOMITES WITH INTERCALATED THIN LAYERS OF SHALE, PURE LIMESTONE, ARGILLACEOUS SANDSTONE, AND ARKOSE.
ARKOSE, ARGILLACEOUS SANDSTONE, AND THIN LAYERS OF CALCAREOUS SHALE.
CALCAREOUS SHALE WITH THIN LAYERS OF NONCALCAREOUS SHALE AND SANDSTONE.
ARKOSE, ARGILLACEOUS SANDSTONE, AND THIN LAYERS OF CALCAREOUS SHALE.
SHALE CONTAINING LENSES AND LAYERS OF ARKOSE AND QUARTZOSE SANDSTONE.
LIMESTONE, DOLOMITE, QUARTZOSE SANDSTONE, ARGILLACEOUS LIMESTONE AND DOLOMITE.
QUARTZOSE SANDSTONE, ARGILLACEOUS SANDSTONE, ARKOSE, AND SHALE. SECTION GRADED LATERALLY IN TO SEQUENCE DOMINATED BY ARKOSE.
STRATIGRAPHY OF INDIVIDUAL UNITS HIGHLY GENERALIZED

ION CHART

ange, Colorado, and probable sedimentary equivalents

other aggregates muscovite formed directly from sillimanite. Muscovite and sericite are more abundant in rocks adjacent to masses of migmatite than at a distance, and the formation of muscovite and sericite seems to be a late process accompanying migmatization and granitization of the rocks southeast of the North Fork fault. Muscovite in oblique plates formed by direct crystallization and not at the expense of finer-grained aggregates. Some sericite is concentrated around small porphyry intrusions of Tertiary age and is unrelated to Precambrian metamorphic processes.

SILLIMANITE: This mineral is abundant in the lower units of the *A* series and forms silky clusters and lenses of needles parallel to the foliation of the enclosing rocks.

MINOR MINERALS: In addition to the minerals mentioned above, a great variety of accessory minerals occurs in practically all rock types. In the lime-silicate rocks of the *A* series notable minor minerals are epidote, zoisite, chondrodite, chlorite, apatite, zircon, magnetite, pyrite, rutile, sphene, garnet, calcite, corundum, ilmenite, and allanite. Accessory minerals in the quartzo-feldspathic or micaceous units of both the *A* series and the *B* series include magnetite, zircon, apatite, sphene, garnet, epidote, and zoisite. Graphite is present in the lower units of the *A* series, especially in rocks containing abundant sillimanite.

Stratigraphy of Premetamorphic Rocks

Table 1 lists chemical analyses and approximate modes for several of the volumetrically important, distinctive rock types of the Hall Valley area. Most samples were collected at a considerable distance from exposures of migmatites and granitic rocks. Sections for micrometric analyses were cut perpendicular to foliation where it is megascopically visible. The approximate estimated volume percentages are given in the modes because the thin sections represent only small portions of the much larger samples used for chemical analysis and are not reliable indicators of the exact mineral composition. Extensive metasomatism or metamorphic segregation outside the migmatized and granitized areas is not indicated, and the bulk chemical compositions of the various layers in the foliated rocks probably remained essentially constant during metamorphism except for the loss of volatile components such as water and carbon dioxide.

Chemical composition does not indicate the classification of the original sedimentary materials because the range of composition of pelitic rocks embraces the compositions of practically all the more easily classified and subdivided psammitic sediments, but correlation of chemical composition with relict fabrics and consideration of the thicknesses, sequence, and associations of the various layers in the metasedimentary units provide a substantial basis for interpretation of both the composition and fabric of the sedimentary rocks before metamorphism. Figure 2 compares the analyses in Table 1 with chemical analyses of several important types of igneous and sedimentary rocks.

The hornblende-plagioclase gneisses and schists associated with quartzo-feldspathic rocks in both the *A* and *B* series formed by recrystallization of calcareous rocks, but, as discussed by Poldervaart (1953, p. 259–274), almost identical hornblendic mineral assemblages can result from metamorphism of either basaltic rocks or impure calcareous sedimentary rocks. Abundant hornblende-plagioclase gneisses and schists of variable composition in thick and thin layers in the lime-silicate units of the *A* series commonly contain quartz and alternate with and grade into layers of calcite, pyroxene rock, quartzite, and quartz-biotite gneiss. These rocks almost certainly formed by metamorphism of stratified calcareous sediments, probably calcareous shales or mudstones. Hornblende-plagioclase gneiss in thin layers in other units of the *A* series appears to have formed from the same kinds of materials. Ratios computed from chemical analyses of lime silicates in the *A* series (Fig. 2, HW,11 F58, WW3, W40, F30) show notable differences for certain combinations of oxides and indicate variations in composition that would be expected in impure, stratified, calcareous sediments. Graywackes of appropriate composition might yield aggregates of hornblende and plagioclase upon recrystallization, and some of the plotted points fall near the graywacke field. Constant association of the lime-silicate rocks with interlayers of abundant calcite seems to indicate that carbonate rocks rather than graywackes were the original materials.

The origin of the very abundant hornblende-plagioclase gneisses and schists of the *B* series is less certain. Relict clastic quartz and zircon and alternation with quartz-biotite gneiss, quartzite, and other originally clastic rocks indicate metamorphic recrystallization of fragmental sedimentary rocks, but chemical analyses (F82, HW100, F38) and thin sections in-

TABLE 1.—CHEMICAL ANALYSES AND MODES OF PRECAMBRIAN METASEDIMENTS
(Excluding migmatized and granitized rocks)
Analyst: O. J. Kim

	F82*	HW100	F38	H39	HW11	F30	F28	G7	H106	W1
SiO_2	49.08	46.93	51.01	66.74	36.81	58.23	75.10	75.00	62.22	82.23
TiO_2	2.10	2.91	1.13	1.24	1.35	2.77	0.38	1.79	1.30	0.73
Al_2O_3	13.38	14.59	14.21	14.29	7.12	13.89	13.62	12.63	19.32	10.61
Fe_2O_3	2.34	2.94	2.54	2.27	2.16	3.04	0.76	0.90	1.14	0.99
FeO	8.80	8.25	7.50	2.89	7.06	6.55	0.94	3.46	3.29	0.23
MnO	0.21	0.17	0.15	0.02	0.11	0.08	Tr.	0.04	0.01	None
MgO	7.73	6.92	5.97	0.49	8.14	3.18	0.33	0.96	1.66	0.18
CaO	11.08	11.34	12.12	4.97	25.97	6.27	1.80	1.10	1.16	0.13
Na_2O	2.98	3.01	2.86	4.22	0.99	4.40	3.69	1.31	2.83	0.75
K_2O	0.60	1.00	0.57	0.56	0.57	0.79	3.03	2.21	6.10	2.55
H_2O-	0.07	0.03	0.06	0.02	0.02	0.04	0.02	0.04	0.05	0.07
H_2O+	0.27	0.56	0.50	0.84	0.62	0.53	0.58	0.83	1.13	1.38
P_2O_5	0.09	0.17	0.19	0.19	0.09	0.21	0.04	0.11	0.08	0.18
CO_2	1.55	1.23	1.40	1.14	8.95	0.10	—	—	—	—
Total	100.28	100.05	100.21	99.88	99.96	100.08	100.29	100.38	100.29	100.03

MODES
(By volume)

Sample no.	1–10%	10–20%	20–30%	30–40%	40–50%	More than 50%
F82	Quartz Biotite Diopside			Plagioclase		Hornblende
HW100	Chlorite Magnetite			Plagioclase		Hornblende
F38	Quartz Diopside		Plagioclase			Hornblende
H39	Epidote Ilmenite	Hornblende	Quartz			Plagioclase
HW11	Zoisite Sphene	Calcite	Hornblende			Diopside
F30	Quartz Biotite Corundum Magnetite			Hornblende		Plagioclase
F28	Biotite		K feldspar Plagioclase			Quartz
G7	Plagioclase Muscovite Sillimanite	Biotite				Quartz
H106	Muscovite Sillimanite	Plagioclase Biotite	Quartz		K feldspar	
W1	Andalusite Pyrite (hydrothermal)		Sericite			Quartz

dicate a uniformity of composition that is not consistent with the assumption that the rocks were derived from ordinary impure calcareous rocks. Layers of calcite and pyroxene that are common in the hornblendic rocks in the lime-silicate units of the *A* series are absent. Compared with a hornblende-plagioclase gneiss (F30) from a thin, homogeneous layer in a quartz-biotite gneiss in the *A* series the hornblende-plagioclase gneisses of the *B* series are lower in Al_2O_3 and alkalies and cluster near points for rocks of basaltic or tholeiitic composition (Fig. 2). A basaltic composition is further confirmed by calculation of the norms and classification of the rocks by the C.I.P.W. system (Washington, 1917).

The association of numerous very thin layers of metamorphosed rocks of basaltic composition with metamorphosed quartzo-feldspathic rocks that probably were sandstones, arkoses, and related argillaceous rocks before metamorphism suggests strongly that the hornblende-plagioclase gneisses and schists of the *B* series were also originally clastic and probably pyroclastic. Some of the thick, more uniform layers may have been basalt flows, but the thin layers alternating with quartz and feldspar-rich rocks must have been fragmental. Kim (1954, Ph.D. thesis, Univ. Colorado), using fewer data, concluded that the hornblende-plagioclase schists and gneisses in both the *A* and *B* series formed from impure, calcareous sediments.

The lower metasedimentary units of the *B* series and several units of the *A* series contain dikes and sills of hornblendic rocks which were metamorphosed at the same time as the enclosing rocks. Mineralogically the hornblendic rocks are much the same as many layers of hornblende-plagioclase gneisses and schists in the *B* series. Although the dikes and sills are younger than the rocks they cut, they might indicate a prolonged period of igneous activity that coincided in part with the time interval of deposition of the sediments of the *B* series.

Table 2 correlates the analyzed metamorphic rocks with the probable original sediments from which they were derived. Plate 1 is a chart in which the units of the *A* series and the *B* series are correlated with a highly generalized sedimentary sequence.

The units in the *A* series are interpreted as the result of metamorphism of a thick, complexly interstratified sequence of shales, sandstones, and limestones such as might have been deposited in an intermittently subsiding, relatively shallow marine basin. Sedimentation was interrupted by uplift and erosion and then was reinitiated with deposition of clastic quartzo-feldspathic materials interstratified with basaltic, probably pyroclastic aggregates. The sedimentary record seems to indicate a gradual mild increase in tectonic disturbance beginning at the time of deposition of the upper units of the *A* series and reaching a maximum during the formation of the Hall Valley unconformity and deposition of younger, coarsely clastic sedimentary rocks.

Mineral Assemblages and Facies Classification

Figure 3 shows the chemical analyses in Table 1 plotted on an ACF diagram for the sillimanite-almandine subfacies of the almandine amphibolite facies as described by

Table 1.—Continued

B series

F82. Hornblende-plagioclase gneiss (phb_2). West of Gibson Lake, sec. 26, R. 76 W., T. 6 S.

HW100. Hornblende-plagioclase gneiss (hp). South of Missouri Mine, sec. 14, R. 76 W., T. 6 S.

F38. Hornblende-plagioclase gneiss (hp). East of Gibson Lake, sec. 26, R. 76 W., T. 6 S.

H39. Quartz-plagioclase-hornblende gneiss (phb_1). Near Whale Mine, sec. 14, R. 76 W., T. 6 S.

A series

HW11. Layered calcitic rock in lime-silicate rocks (ls_3). Ridge between Lake Fork and Hall Valley, sec. 25, R. 76 W., T. 6 S.

F30. Hornblende-plagioclase gneiss from layer in quartz-biotite gneiss (qb_2). Ridge between Lake Fork and Hall Valley, sec. 25, R. 76 W., T. 6 S.

F28. Quartz-biotite gneiss (qb_1). Near Junction of Hall Valley and Lake Fork, sec. 31, R. 75 W., T. 6 S

G7. Biotite-sillimanite schist (bsi). Head of Bruno Gulch, sec. 18, R. 75 W., T. 6 S.

H106. Augen biotite-sillimanite gneiss (bsi). Hall Valley, sec. 24, R. 76 W., T. 6 S.

W1. Quartz schist (qs). Handcart Gulch, sec. 19, R. 75 W., T. 6 S.

* Locations of analyzed samples are shown on Plate 4.

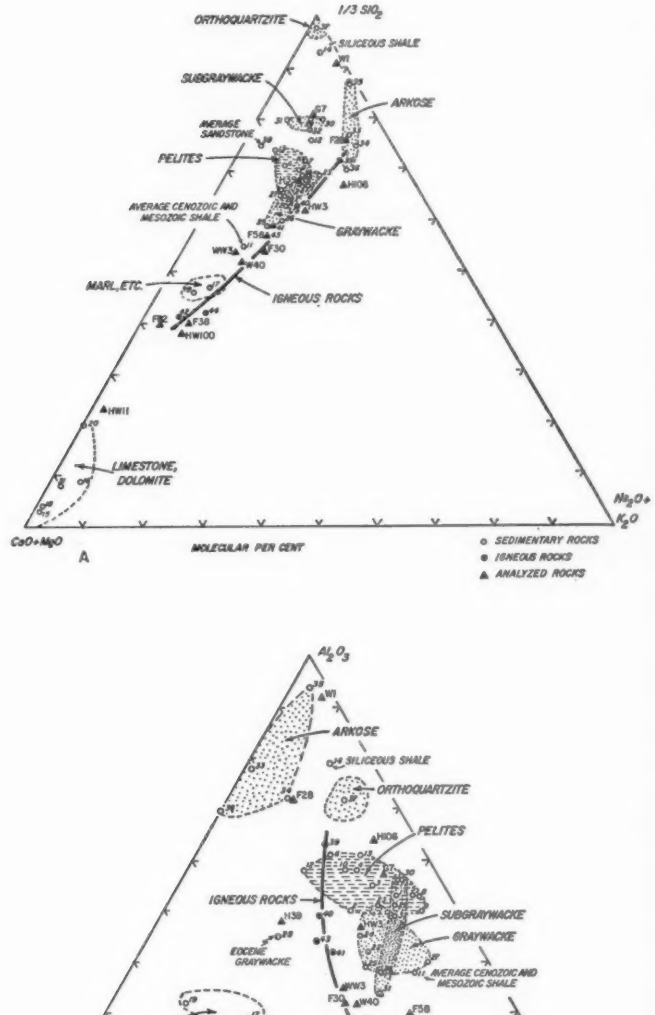


FIGURE 2.—TERNARY DIAGRAMS FOR HALL VALLEY

Analyses from Table 1 and from published sources in accompanying list. Points for W40, WW3, HW3 and F58 from unpublished partial analyses of lime-silicate rocks in *A* series by R. L. Kinnaman.

Sedimentary and Igneous Rock Analyses Plotted on Figure 2

Pelitic rocks

1. Average of 155 pelitic rocks (Shaw, 1955, p. 1615)
2. Average of 78 shales (Clarke, 1924, p. 30)
3. Average of 51 "red marine clays" (Clarke, 1924, p. 518)
4. Average of 52 "green and blue marine shales" (Clarke, 1924, p. 518)
5. Average of 22 slates (Clarke, 1924, p. 631)
6. Average of 36 roofing slates (Eckel, 1904, p. 26)
7. Average of 27 slates and phyllites (Lapadu-Hargues, 1945, p. 261–262)
8. Average of 61 slates (Poldervaart, 1955, p. 136)
9. Average of 33 Precambrian slates (Nanz, 1953, p. 57)
10. Average of 51 Paleozoic shales (Clarke, 1924, p. 552)
11. Average of 27 Mesozoic and Cenozoic shales (Clarke, 1924, p. 552)
12. Average of 236 Mississippi Delta silts (Clarke, 1924, p. 509)
13. Average of 7 bentonite samples (Spence, 1914, p. 14)
14. Siliceous Mowry shale, Black Hills (Rubey, 1929, p. 157)

Calcareous rocks

15. Average of 345 limestones (Clarke, 1924, p. 518)
16. Cement rock, Lisbon, Ohio (Stout and Lamborn, 1924, p. 195)
17. Marine marlstone (calcareous shale), Butler County, Ohio (Stout, 1941, p. 114)
18. Niagaran dolomite (Fisher, 1925, p. 34)
19. Calcareous shale, Pueblo County, Colorado (Clarke, 1924, p. 552)
20. Calcareous shale, Mount Diablo, California (Clarke, 1924, p. 552)
21. Average of 498 limestone used for building purposes (Clarke, 1924, p. 564)

Graywacke as identified by various authors

22. Average graywacke (Pettijohn, 1949, p. 250)
23. Average of 3 Franciscan series graywackes (Taliaferro, 1943, p. 136)
24. Average of 2 graywackes from Marlborough, New Zealand (Henderson, 1935, p. 15)
25. Average of 3 Archean graywackes (Grout, 1929, p. 997)
26. Average of 3 Archean graywackes (Todd, 1928, p. 20)
27. Archean graywacke, Manitou Lake, Ontario (Pettijohn, 1949, p. 250)
28. Eocene graywacke, Washington (Pettijohn, 1949, p. 250)

Subgraywacke as identified by various authors

29. Subgraywacke near Mena, Arkansas (Pettijohn, 1949, p. 256)
30. Subgraywacke near Hurley, Wisconsin (Diller, 1898, p. 87)
31. Subgraywacke, Loon Lake, Minnesota (Grout and Schwartz, 1933, p. 22)
32. Average subgraywacke (Pettijohn, 1949, p. 256)

Arkose as identified by various authors

33. Average arkose (Pettijohn, 1949, p. 259)
34. Lower Old Red sandstone, Scotland (Pettijohn, 1949, p. 259)
35. Torridon sandstone, Scotland (Pettijohn, 1949, p. 259)
36. Portland stone (Merrill, 1897, p. 420)

Orthoquartzite

37. Average of 4 orthoquartzites (Pettijohn, 1949, p. 241)

"Sandstone"

38. Average of 253 sandstones (Clarke, 1924, p. 30)

Igneous rocks

39. Average of 546 granites (Daly, 1933, p. 9)
40. Average of 40 granodiorites (Daly, 1933, p. 15)
41. Average of 55 quartz diorites (Daly, 1933, p. 15)
42. Average tholeiite (Poldervaart, 1955, p. 134)
43. Average of 87 andesites (Daly, 1933, p. 16)
44. Average of 198 basalts (Daly, 1933, p. 17)

Fyfe, Turner, and Verhoogen (1958, p. 230). The diagram is for rocks containing excess SiO_2 and K_2O and represents equilibrium mineral assemblages formed at the highest grades of muscovite replace sillimanite indicate partial retrogression.

The analyzed rocks plotted in Figure 3 are peripheral to areas of extensive migmatization,

TABLE 2.—METAMORPHIC ROCKS AND SEDIMENTARY EQUIVALENTS

Metamorphic rock		Original sedimentary rock
	B series	
F82	Hornblende-plagioclase gneiss	Clastic basaltic material
HW100	Hornblende-plagioclase gneiss	Clastic basaltic material
F38	Hornblende-plagioclase gneiss	Clastic basaltic material
H39	Quartz-plagioclase-hornblende gneiss	Mixture of clastic materials of basaltic composition and quartzose, sandy components
	A series	
HW11	Banded calcitic rock in lime-silicate unit	Arenaceous dolomitic limestone
F30	Hornblende-plagioclase schist in quartz-biotite gneiss	Calcareous shale or mudstone
F28	Quartz-biotite gneiss	Arkose
G7	Biotite-sillimanite gneiss	Shale or mudstone rich in clay minerals; composition similar to graywacke in part
H106	Augen biotite-sillimanite gneiss	Shale or mudstone containing quartz and feldspar-rich layers; K feldspar may have been introduced.
W1	Quartz schist	Quartz-rich sandstone with clay mineral matrix; near orthoquartzite in composition

normal regional metamorphism. Fair agreement exists between the theoretical assemblages and the actual assemblages (Table 3). In each theoretical assemblage quartz and potassium feldspar are possible additional members.

The complexity of the original rocks and the fact that not all the rocks have excess SiO_2 (notably HW11) and that some of the rocks are deficient in K_2O and mafic components (especially W1) help to explain the disparity between the actual and theoretical assemblages. Abundant biotite and only very small amounts of almandine may be an expression of a low FeO-MgO ratio (Turner, 1948, p. 85), or, as seen in some thin sections, growth of biotite at the expense of original almandine. Pyroxene (diopside and augite) shows all degrees of alteration to hornblende and indicates introduction of hydroxyl and mafic components leading to a state of disequilibrium. The local presence of chlorite and epidote formed from calcareous minerals and the fact that sericite and

and probably the same fluids that promoted the migmatization locally penetrated the areas surrounding the migmatite and to a limited extent promoted various changes, especially uralitization of pyroxenes and formation of muscovite at the expense of sillimanite. Late sparse muscovite, oblique to the conspicuous bedding-plane foliation, indicates shearing stresses before or during retrogression.

MIGMATITES AND GRANITIC ROCKS

General Statement

The Precambrian sedimentary rocks in the southeast portion of the Hall Valley area were largely converted into migmatites of complex structure and lithology and into lenticular bodies of granitic rocks that seem to have formed by metasomatism and local mobilization. Migmatization and granitization are concentrated southeast of North Fork fault,

but the solutions promoting migmatization moved along and crossed the fault and spread northwestward in several units of the *A* series (Pl. 4). Most migmatization and granitization

Migmatites

The migmatites consist of several varieties of complexly interlayered, more or less gneissoid

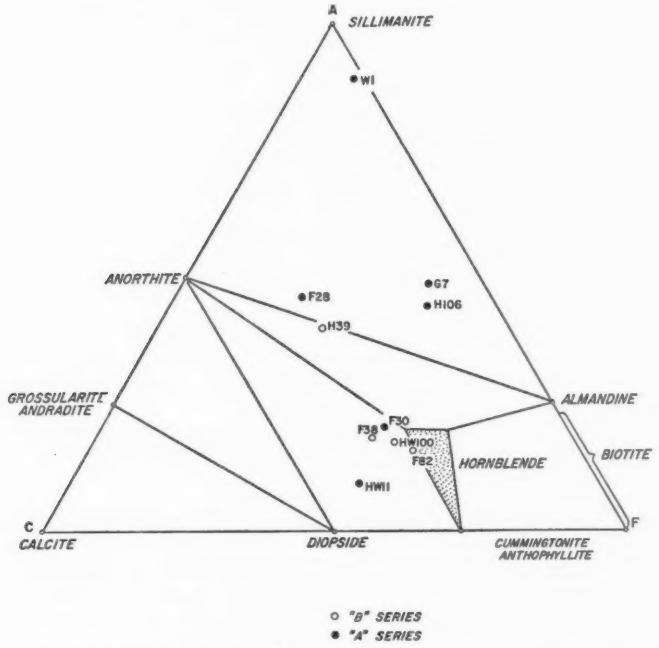


FIGURE 3.—ACF DIAGRAM FOR SILLIMANITE-ALMANDINE SUBFACIES

Points of diagram calculated from analyses in Table 1. Triangular diagram revised from diagram by Fyfe, Turner, and Verhoogen (1958, p. 231). For rocks with excess SiO_2 and K_2O.

are confined to rocks that originally were argillaceous and/or quartzo-feldspathic. Quartz-biotite gneiss, quartz schist, and biotite-sillimanite gneiss were particularly susceptible to reconstitution. Lime-silicate rocks, amphibole schists and gneisses, and quartzites resisted migmatization and granitization and remained as relatively unaltered layers in otherwise extensively transformed rock masses.

Migmatization and granitization were later than the dislocations that produced North Fork fault and may have preceded or accompanied the intrusion of a body of Boulder Creek granodiorite into the northeast portion of the Hall Valley area.

Table 4 lists chemical analyses and modes of several representative samples of migmatites and granitic rocks.

and schistose rocks. Gneissic to massive granitic rocks, aplites, and pegmatites are intimately associated with mica-rich quartz-biotite gneiss, biotite schist, hornblende-plagioclase gneiss, lime hornfels, and gray to nearly black quartzite. Gradational contacts between layers are common, and microscopic fabrics indicate pervasive metasomatism. Compared to the nonmigmatized rocks northwest of North Fork fault dark layers are darker and generally richer in dark minerals, and light layers are lighter and contain smaller amounts of dark components. Many essentially monomineralic aggregates of biotite or hornblende within the migmatites indicate extensive metamorphic segregation and considerable mobility and migration of the components of the minerals.

Complex folds that have a variety of orientations, parallel and crosscutting aplites and

pegmatites, and thickened or attenuated layers suggest considerable plasticity in the migmatites at the time of formation.

patches of orthoclase. Most of the microcline that is in contact with plagioclase is rimmed by a highly sodic feldspar. The plagioclase is albite

TABLE 3.—ACTUAL AND THEORETICAL MINERAL ASSEMBLAGES

For rocks with excess K_2O and SiO_2 in the sillimanite-almandine subfacies of the almandine amphibolite facies. Minerals in parentheses are possible additional phases.

	Actual assemblage	Theoretical assemblage
	B series	
F82	Hornblende (58.2), plagioclase (34.8), biotite (2.4), diopside (1.4), quartz (2.8)	Hornblende, plagioclase, diopside, (quartz)
HW100	Hornblende (57.4), plagioclase (38.7), chlorite (1.6), quartz (0.4)	Same as F82
F38	Hornblende (63.1), plagioclase (26.1), diopside (7.6), quartz (1.5)	Same as F82
H39	Hornblende (13.0), plagioclase (57.0), biotite (0.2), epidote (2.0), quartz (25.0)	Hornblende, plagioclase, almandine, (quartz), (biotite)
	A series	
HW11	Hornblende (29.8), plagioclase (0.1), diopside (52.4), zoisite (1.6), scapolite (0.5), corundum (0.5)	Hornblende, plagioclase, diopside
F30	Hornblende (33.8), plagioclase (51.8), biotite (2.6), quartz (8.4), corundum (1.5)	Hornblende, plagioclase, diopside, (quartz)
F28	Plagioclase (23.4), biotite (2.5), microcline (21.8), quartz (52.1)	Plagioclase, almandine, (biotite), sillimanite, (K feldspar), (quartz)
G7	Plagioclase (7.8), biotite (15.2), muscovite (3.9), diopside (0.3), sillimanite (8.2), quartz (64.5)	Same as F28
H106	Plagioclase, biotite, muscovite, sillimanite, microcline, quartz	Same as F28
W1	Sericite (after sillimanite) (21.5), andalusite (1.6), quartz (75.0)	Same as F28

Granitic Rocks

The granitic rocks are light gray or pinkish gray, coarse- to sugary-grained, massive to slightly gneissoid, and consist of quartz, feldspars, micas, and minor accessory minerals. Lenticular inclusions of biotite gneiss are abundant and grade into the enclosing granitic rocks. Microscopically the fabric is granoblastic to pseudocataclastic. Quartz is in fractured sutured grains, in grains that have simple contacts, and in smaller grains penetrating or enclosed by mica, plagioclase, or microcline. Myrmekite and graphic intergrowths are abundant. Microcline appears to have formed by inversion of apparently untwinned orthoclase, and many grains contain cores or irregular

and oligoclase and is cloudy and sericitized. As in the adjacent migmatites two types of biotite are present: a variety of frayed, irregular, turbid aggregates, and a clear variety in distinct plates. Muscovite is a minor but widespread mineral that forms parallel and oblique intergrowths with the clear biotite.

Migration of Elements

The migmatites and granitic rocks were formed in an environment of extensive migration and redistribution of the original components of the rocks and probable introduction of additional components. Conspicuous bedding-plane foliation in the metamorphic rocks unaffected by migmatization northwe

TABLE 4.—CHEMICAL ANALYSES AND MODES OF GRANITIC ROCKS AND MIGMATITES
Analyst: O. J. Kim

	G18	S18	PS65	B32	PS11	PS4	WW50
SiO_2	77.65	75.47	73.20	73.51	75.37	75.72	72.47
TiO_2	0.49	0.31	0.48	0.34	0.35	0.62	0.69
Al_2O_3	12.31	13.86	15.12	15.30	14.28	13.12	14.19
Fe_2O_3	0.82	0.22	0.78	0.46	0.82	1.19	1.74
FeO	0.33	0.77	0.54	0.50	0.54	1.44	1.36
MnO	None	None	None	None	Tr.	Tr.	Tr.
MgO	0.32	0.17	0.19	0.10	0.55	0.71	1.00
CaO	0.93	0.86	0.81	0.78	3.23	1.85	2.62
Na_2O	2.78	3.42	3.85	4.42	4.20	4.20	3.88
K_2O	4.48	5.01	5.81	5.25	0.82	0.88	1.13
H_2O-	0.07	0.02	0.05	0.04	0.02	0.01	0.07
H_2O+	0.36	0.24	0.37	0.46	0.27	0.23	0.83
P_2O_5	0.16	0.10	0.06	0.09	0.03	0.05	0.06
CO_2	None	None	None	None	None	None	None
Total	100.70	100.45	101.26	101.25	100.48	100.02	100.04
MODES							
Quartz	48.4	38.9	32.2	37.2	42.0	69.8	37.8
Plagioclase	13.1	30.1	23.4	29.4	50.1	21.2	50.2
K feldspar	31.3	24.9	40.0	23.1	1.6		0.8
Biotite	4.5	5.1	2.8	3.3	3.9	9.0	7.8
Muscovite	0.4	0.9	1.4	7.0	0.6		1.7
Hornblende					1.0		
Clinopyroxene					0.8		
Magnetite	2.1	0.1	0.2				1.1

G18. Granitic rock. South of Bruno Gulch, sec. 15, T. 6 S., R. 75 W.
S18. Granitic rock. Sawmill Gulch, sec. 28, T. 6 S., R. 75 W.
PS65. Granitic rock. South side, North Fork South Platte River, T. 6 S., R. 75 W.
B32. Granitic rock. Head of Beaver Creek.
PS11. Quartz-biotite gneiss from migmatite. One mile south of junction of Lake Fork and North Fork.
PS4. Migmatite. Three quarters of a mile southwest of junction of Lake Fork and North Fork.
WW50. Quartz-biotite gneiss from migmatite. Handcart Gulch, sec. 19, T. 6 S., R. 75 W

of North Fork fault is practically obliterated southeast of the fault except in layers of calcic and highly quartzose rocks that resisted migmatization and granitization. Parallelism of gneissic fabrics in the migmatites and granitic rocks with bedding-plane foliation in resistant layers and an abundance of rocks that might be classified as injection gneisses or *lit-par-lit* gneisses suggest that migration of components and metasomatism resulted mainly from movement of solutions along foliation planes of previously metamorphosed rocks. The metamorphic rocks outside the areas of migmatization and granitization seem to have recrystallized under essentially "dry" conditions, compared to the migmatites and granitic rocks.

The granitic bodies formed from more intensive metasomatism than prevailed in the migmatites, and variations in mineral assemblages and composition of the migmatites appear to be in part a function of distance from the granitic bodies. Quartz-biotite gneiss is abundant in both the migmatites and the nonmigmatized rocks, and comparisons of mineral assemblages from several exposures indicate that: (1) plagioclase in migmatites near granitic bodies is more sodic than at a distance, (2) a

frayed, turbid type of biotite is present in both migmatite and granitic rocks but appears to decrease in amount away from the granitic rocks, (3) microcline in the migmatites decreases in amount and grain size away from the granitic bodies, where it is a dominant constituent, and (4) quartz appears to be the same in both migmatites and granitic rocks.

Dark minerals are concentrated in the rocks near and within the outer fringes of migmatized areas. The quartz schist unit of the *A* series is normally a light-colored rock outside the migmatized areas, but as the unit is traced to the southeast in the direction of the migmatites it gradually becomes darker and richer in mafic components, especially biotite and amphibole. Bedding-plane foliation is distinct until it is obliterated in the migmatites. Similar changes in biotite-sillimanite gneiss and quartz-biotite gneiss units suggest that the outer portion of the migmatite zone and a zone of indefinite width outside the migmatites have some of the characteristics of a basic front resulting from movement of cafemic components outward from centers of granitization.

Chemical analyses of migmatites and granitic rocks in Table 4 and selected analyses of rocks outside the areas of migmatization from Table 1 were plotted on the diagram in Figure 4. Analyses for the migmatites and granitic rocks form clusters of points and indicate approximate chemical similarity for samples of each rock type. Points for analyses of hornblende-rich rocks outside the migmatized areas were

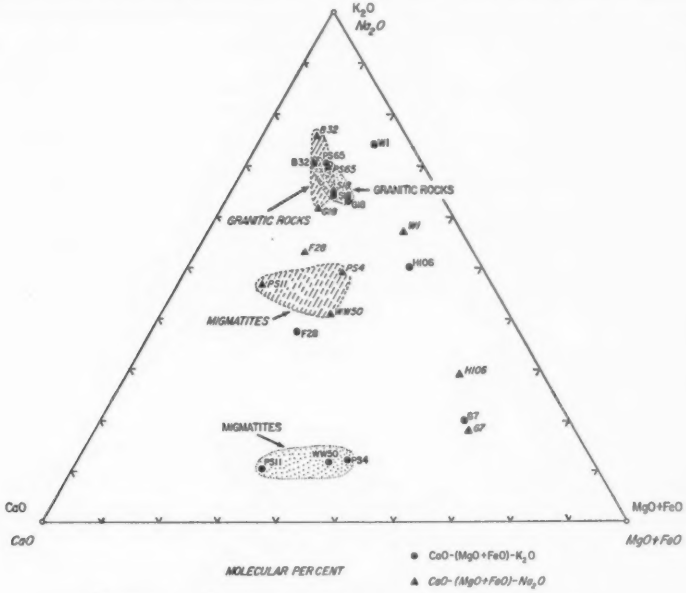


FIGURE 4.—TRIANGULAR PLOT OF CHEMICAL ANALYSES

Shows migmatites, granitic rocks, and the metasedimentary rocks from which the migmatites and granitic rocks probably were derived by metasomatism. Computed from analyses in Table 4 and selected analyses from Table 1.

PLATE 2.—LIME-SILICATE ROCKS

FIGURE 1.—Weathered lime-silicate rock. Ridge between Hall Valley and Handcart Gulch. Rock consists of hornblende-plagioclase gneiss, quartzite, and layers of calcite that have been partly dissolved by weathering. Layering is parallel to original bedding.

FIGURE 2.—Boudins in uppermost lime-silicate unit of the *A* series. Lake Fork trail. Rock contains layers of calcite, quartzite, and micaceous, hornblendic, and quartzo-feldspathic rocks. Layering is parallel to original bedding. Boudins consist of diopside aggregates rimmed by hornblende.

FIGURE 1

FIGURE 2

LIME-SILICATE ROCKS

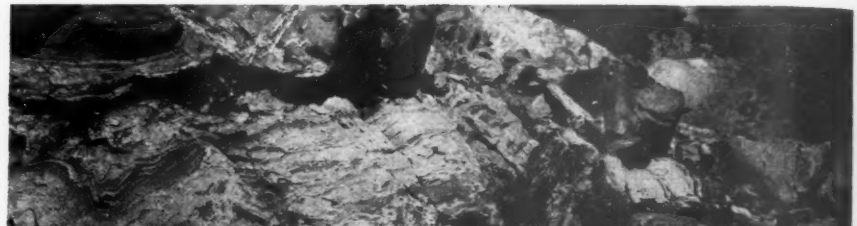


FIGURE 1

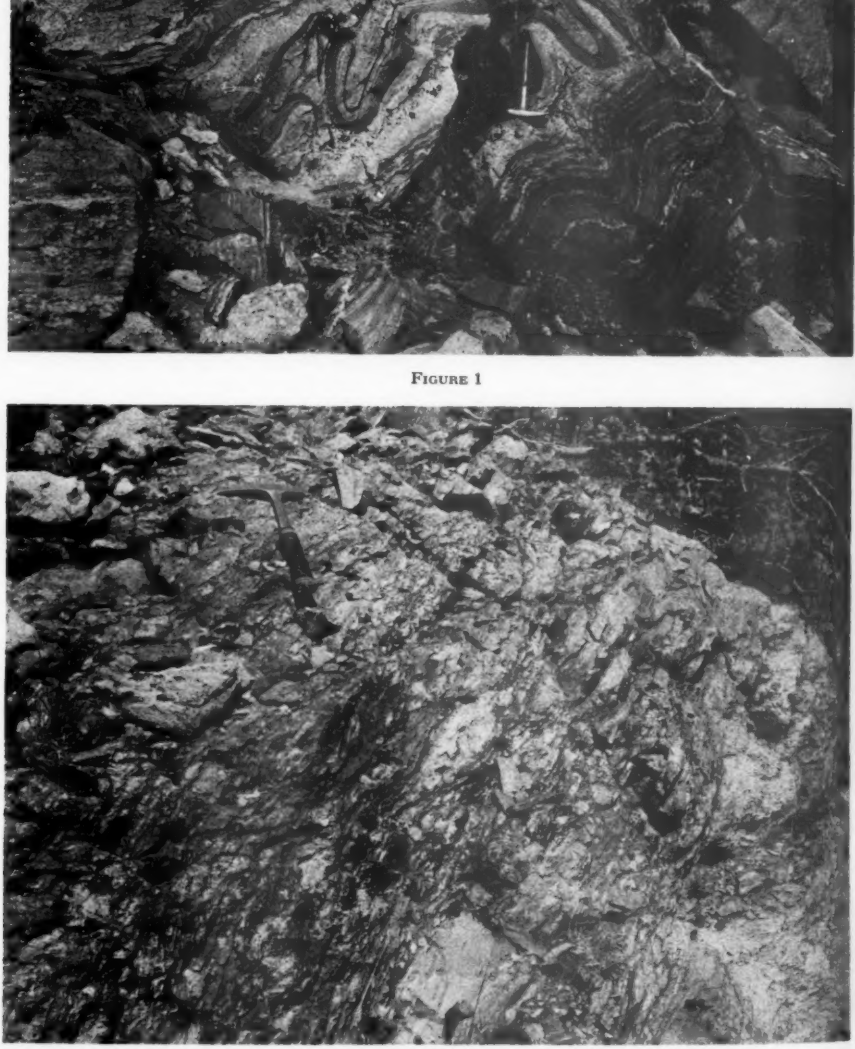


FIGURE 2

FOLDED AND FAULTED METAMORPHIC ROCKS

not plotted because such rocks resisted metasomatism in even the most intensely migmatized rocks and remain as relatively unaltered layers. The diagram, by elimination of the hornblendic rocks, compares the migmatites and granitic rocks with the volumetrically important varieties of the micaceous and quartzofeldspathic metamorphic rocks that appear to have been most susceptible to metasomatic transformation.

Too few analyses are available to describe systematic chemical changes resulting from metasomatism of specific original rock types, but correlation of chemical data with petrographic and field data indicates the nature of certain gross changes. The granitic rocks are notably deficient in MgO+FeO and enriched in K_2O and Na_2O, compared with several of the probable original rocks; this indicates that granitization was in part the result of introduction of alkalies and removal of femic components. The rock type outside areas of migmatization and granitization most similar to the migmatites and granitic rocks in K_2O and Na_2O and other components is quartz-biotite gneiss (F28). Most of the migmatites and granitic rocks probably formed from quartz-biotite gneiss, not only because it was very abundant but also because its conversion into granitic rock and migmatite would require fewer chemical adjustments than in other rock types. Biotite-sillimanite schists and gneisses and quartz schist (G7, H106, W1) that were converted into granitic rocks required introduction of both K_2O and Na_2O to form feldspathic rocks containing abundant alkali feldspars.

Sampling of the complex migmatites was much more difficult than for the granitic rocks, and chemical and mineralogical changes resulting from migmatization are not so obvious as for the granitic rocks. Addition of alkalies, especially K_2O, to the migmatites near the granitic bodies is indicated by chemical analyses, the distribution of alkali feldspars peripheral to the granitic bodies, and alteration of sillimanite to muscovite and sericite. Femic components displaced from areas of granitic rocks and migmatites probably diffused through the migmatites and in part were concentrated in dark rocks within and outside the migmatized areas. In the granites CaO is present in about the same ratios to alkalies and MgO +FeO as in the original rocks, but actual amounts as measured by weight percentages are less in the granitic rocks than in the migmatites. A gradation to more calcic plagioclases and more abundant dark minerals in a direction away from the granitic bodies suggests migration of calcium toward the outer portion of the migmatized zone.

Boulder Creek Granodiorite and Silver Plume Granite

A body of gray, medium- to coarse-grained granodiorite resembling Precambrian Boulder Creek granodiorite at the type locality (Lovering and Goddard, 1950, p. 25) cuts across the regional layering in the migmatites and granitic rocks in the northeast portion of the Hall Valley area. The granodiorite is massive to slightly gneissoid and contains quartz, microcline, plagioclase, and abundant biotite. Locally the granodiorite grades into a pinkish, coarse-grained granite that superficially resembles the Pikes Peak granite (Lovering and Goddard, 1950, p. 28). Migmatization in the Hall Valley area may be a peripheral manifestation of the emplacement of the Boulder Creek granodiorite.

Several small masses of granitic rocks in the Hall Valley area resemble Silver Plume granite (Lovering and Goddard, 1950, p. 28) but grade into granitic and aplitic rocks formed by metasomatism of the metasedimentary rocks. The Silver Plume granite is a gray to medium-pinkish-gray medium-grained biotite granite. Most of the bodies in the area are lenticular and grade almost imperceptibly into migmatized schists and gneisses. Outside the Hall Valley area to the east and south crosscutting bodies of typical Silver Plume granite occur in migmatites that appear to be associated in space and time with the intrusion of the granite.

In the Harold D. Roberts tunnel, 3–5 miles

Plate 3.—Folded and faulted metamorphic rocks

Figure 1.—Folding in plagioclase-hornblende-biotite gneiss unit of *B* series. North side of Gibson Lake. Dark rocks are hornblende-rich. Light rocks are quartzo-feldspathic and appear to have been partially mobilized and to have flowed. Layering in dark rock parallels original stratification.

Figure 2.—Flaser gneiss and breccia in North Fork fault. East end of ridge between Hall Valley and Handcart Gulch. Layering in gneiss dips to the northwest.

northeast of Hall Valley, large bodies of Boulder Creek granodiorite and Silver Plume granite have been encountered, and extensive migmatites are associated with each type of rock. Dikes of Silver Plume granite, or a granite closely resembling Silver Plume granite, intersect the Boulder Creek granodiorite and suggest that the Silver Plume is younger. The migmatites in the Hall Valley area and adjacent areas could have formed during at least two different times.

Pegmatite and Aplite

Pegmatite and aplite are abundant in the migmatites in both conformable and crosscutting bodies. Some of the pegmatite and aplite are slightly gneissoid and under the microscope show pseudocataclastic fabrics, myrmekitic and graphic intergrowths, and other features that suggest a metasomatic origin. A few of the crosscutting bodies appear to have developed from metasomatism localized along fractures, but other bodies dislocated the wall rocks and probably formed by intrusion and crystallization of mobilized rocks.

Pegmatites and aplites are locally abundant in the metamorphic rocks at a considerable distance from the centers of migmatization and granitization and have no apparent connection with the large masses of migmatite and granitic rocks southeast of North Fork fault. These isolated pegmatites and aplites appear to have been generated locally from layers of quartzofeldspathic composition in the schists and gneisses. Some generally conformable layers of pegmatite and aplite in the nonmigmatized metamorphic rocks form dikes in brittle adjacent rocks such as quartzite and hornblende gneiss. Many conformable pegmatite and aplite layers in which no gneissic structure is visible grade laterally or vertically into augen gneisses containing feldspar lenses in a matrix of mica, quartz, and feldspar. The pegmatites and aplites probably resulted from partial to complete mobilization and viscous flow of layers of appropriate original composition.

Precambrian Dikes and Sills

The metasedimentary rocks of the *A* and *B* series contain several small mafic dikes which have been metamorphosed into schistose and spotted aggregates of amphibole and calcic plagioclase which have the same mineralogical composition as many of the layers of hornblende-plagioclase gneiss and schist in the *B* series. Apophyses of some of the dikes penetrate the metasedimentary rocks as thin sills. A conformable lens, nearly 300 feet thick and consisting of black, homogeneous amphibolite, is exposed in the cliffs north of the Whale mine at the head of Hall Valley and is interpreted as a metamorphosed sill, or, possibly, as a flow or series of flows incorporated by the sediments of the *B* series before metamorphism.

Tertiary Igneous Rocks

Dikes and small irregular bodies of unmetamorphosed diabase, felsite, and felsite porphyry have intruded the metamorphic rocks of the Hall Valley area and probably are related to the igneous rocks in other parts of the northeastward-trending porphyry and mineral belt of the Front Range. Sericitization and pyritization are conspicuous in and near some of the intrusions, especially near Red Cone peak in the northern part of the Hall Valley area.

Structural Geology

General Statement

Major structural features resulting from Precambrian deformation of the rocks in the northwest and central portions of the Hall Valley area are the Handcart anticline and the North Fork fault (Pl. 4). Numerous smaller folds and faults are subsidiary to the larger structures. Fabrics of the rocks indicate that the sedimentary rocks were deformed extensively before metamorphic reconstitution reached a maximum. In the later stages of metamorphism deformation and recrystallization both contributed to the development of the fabrics. Southeast of the North Fork fault widespread deposits of slide rock and glacial till and a dense forest cover prevent interpretation of the probably complex structures in an area consisting mostly of granitic rocks and migmatites.

Fabric and Composition

Fabric bears a direct relationship to the chemical and mineralogical composition of the metamorphic rocks in the Hall Valley area. Sedimentary layers recrystallized into lime-silicate rocks, quartzites, and hornblende schists and gneisses preserve most of their original thicknesses and delineate the relatively simple gross features of the regional structure. Many rocks rich in mica were deformed by thickening

or attenuation into intricately folded masses. Boudins of brittle rocks are numerous in many of the micaceous layers and in the lime-silicate layers. Initially shaly or quartzo-feldspathic rocks appear to have been more susceptible to mobilization and plastic flow from elevation of temperature than the highly calcic and quartzose rocks (Pl. 3, fig. 1). In areas of migmatite generally concordant bodies of aplite and pegmatite commonly grade into micaceous quartzo-feldspathic rocks, but the calcic and quartzose rocks are cut by sharply defined dikes of aplite and pegmatite. Many complex migmatite masses confined between competent layers in crests or troughs of tight drag folds appear to have formed locally by squeezing or partially to completely fused feldspathic rocks.

Handcart Anticline

The Handcart anticline, exposed in Handcart Gulch northwest of the North Fork fault, is a tightly compressed almost isoclinal fold trending N. 25°–30°W. and plunging northwest. The plunge of the fold as indicated by consistently parallel lineation in prismatic minerals and drag folds is near 45°. The axial plane is nearly vertical, and the limbs of the fold are locally complicated by minor folds and faults. The anticline is intersected by the North Fork fault, but the amount and direction of dislocation of the anticline by the fault is not known. Attempts to locate the anticline in the migmatized and granitized rocks southeast of the North Fork fault were unsuccessful because of heavy cover and complex structure.

Minor folds on the limbs of the Handcart anticline are of two types. Most folds in the mica-rich or quartzo-feldspathic rocks are very intricate and unsystematic and appear to have formed by squeezing and nonuniform plastic dislocation between more rigid layers. Layers of quartzite and hornblende gneiss and schist tend to develop simpler, asymmetrical drag folds on both limbs of the larger fold and consistently indicate its anticlinal nature. The axial planes of most of the simpler minor folds are parallel to the axial plane of the major fold, but a few small folds do not conform to the regional pattern and are oblique to the Handcart anticline.

North Fork Fault

The North Fork fault can be traced across most of the Hall Valley area. The fault strikes northeast and probably dips steeply northwest. In the central part of the Hall Valley area the strike of foliation of metamorphic rocks northwest of the fault is almost perpendicular to the strike of foliation of rocks southeast of the fault, and the location of the fault can be determined fairly accurately. Elsewhere the fault is buried by widespread, heavy cover, and its location can only be inferred. Movement along the fault produced flaser gneisses of complicated fabric in a zone at least 200 feet wide and, along much of the fault, probably considerably wider. In a partial exposure of the fault (Pl. 3, fig. 2) at the southeast end of the ridge between Hall Valley and Handcart Gulch the fault contains a breccia of brittle rocks, especially quartzite and quartzo-feldspathic rocks, embedded in a foliated micaceous rock which has flowed around more or less angular, rotated fragments of the breccia. Lenses and streaks of micaceous and quartzose rocks parallel to the fault cut across original foliation of some of the larger fragments in the breccia and appear to be recrystallized mylonite. Several joints parallel to the fault in lime-silicate rocks northwest of the fault contain seams and dikes of aplite and pegmatite. Portions of the gneiss in the fault were migmatized and contain concordant and discordant bodies of aplite and pegmatite which formed after movement along the fault had subsided and tend to obliterate evidences of faulting.

The North Fork fault cuts across the Handcart anticline almost at right angles to the axial plane of the anticline. The amount of displacement along the fault is not known but probably is considerable. The kinds of materials in the fault and the space relationships indicate that the fault formed at depth, later than the deformation that produced the Handcart anticline but before formation of the migmatites and granitic rocks southeast of the fault. The age relationships indicate that the fault is Precambrian.

Cross folds on the limbs of the Handcart anticline northwest of the fault trend approximately parallel to the fault and may have formed at the same time.

Foliation and Cleavage

Conspicuous foliation parallel to bedding of the recrystallized sedimentary rocks northwest of the North Fork fault strikes N. 10°–30°W. in most exposures. Local variations in the attitude of the foliation are seen in a few small cross folds. Southeast of the North Fork fault foliation strikes primarily northeast, almost at

right angles to foliation northwest of the fault. Conspicuous slaty cleavage, of the type that intersects bedding and develops in many metamorphic areas where deformation and recrystallization are simultaneous, is absent here.

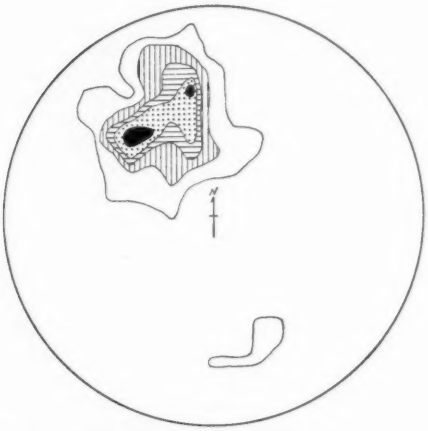


FIGURE 5.—EQUAL-AREA PLOT OF LINEATION IN THE *A* SERIES

Shows 45 average measurements of lineation. Contours 13-10-8-5-2 per cent, maximum 15.5 per cent.

A poorly developed slaty cleavage is seen in some thin sections of rocks adjacent to areas of migmatization and granitization, is oblique to the bedding-plane foliation, and is parallel to sparse muscovite plates of later genesis than the dominant mineral components. Petrofabric analyses indicate that the biotite plates in micaceous rocks are not exactly parallel to the foliation, but this orientation is not apparent in field exposures.

Lineation

Northwest of the North Fork fault mineral lineation is conspicuous in many of the rocks, but some layers containing acicular minerals do not exhibit megascopic parallelism. In most places on the limbs of the Handcart anticline lineation parallels the fold axes of minor drag folds. Below the Hall Valley unconformity in the *A* series 45 average measurements indicate that the Handcart anticline plunges 40°–45° NW. Above the Hall Valley unconformity in the *B* series and on the southwest limb of the Handcart anticline the lineation as determined from 29 average measurements plunges about 48° NW. Some of the minor cross folds on the limbs of the Handcart anticline show poorly developed oblique lineation.

Figures 5 and 6 are equal-area plots of lineation in the *A* and *B* series. Each plotted measurement represents a consistent parallelism of the linear minerals in the general area of the exposure where the measurement was made.

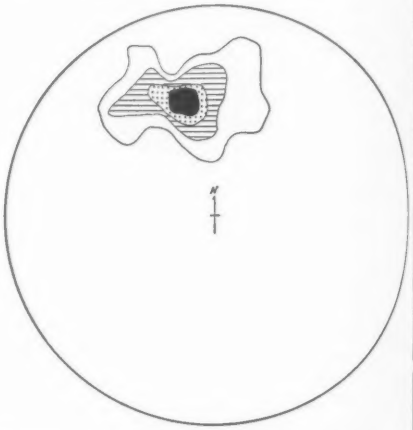


FIGURE 6.—EQUAL-AREA PLOT OF LINEATION IN THE *B* SERIES

Shows 29 average measurements of lineation. Contours 20-15-10-3 per cent, maximum 20.6 per cent.

Lineation in the migmatites and granitic rocks southeast of the North Fork fault is not conspicuous. The few measurements that it was possible to make did not indicate consistent parallelism in the prismatic minerals or minor fold axes.

Joints

Figure 7 is based on measurements of various sets of joints in the *A* series. Maximum concentration corresponds to cross (ac) joints normal to both foliation and lineation. Submaxima correspond to local variations in plunge of lineation and attitude of foliation. Oblique joints are present, but it is not known whether these are related to Precambrian deformation or were superimposed on the rocks during later unrelated movements, such as those that accompanied Laramide orogeny. Figure 8 shows the attitudes of conspicuous joints in the *B* series and again indicates a predominance of cross (ac) joints with fewer oblique joints.

FIGURE 7.—EQUAL-AREA PLOT OF JOINTS IN THE *A* SERIES

Shows 221 poles of joints. Contours 6-4-2-1 per cent, maximum 6.3 per cent.

FIGURE 8.—EQUAL-AREA PLOT OF JOINTS IN THE *B* SERIES

Shows 100 poles of joints. Contours 8-6-4-2-1 per cent, maximum 10 per cent.

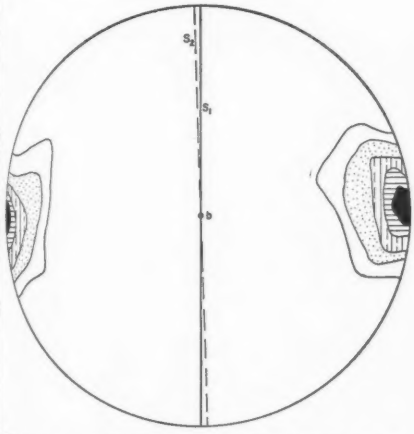


FIGURE 9.—EQUAL-AREA PLOT OF BIOTITE IN THE *A* SERIES

Shows 160 poles of cleavage in biotite in biotite schist (G6). Rotated to make lineation polar. Contours 20-15-10-5-2 per cent, maximum, 21.8 per cent.

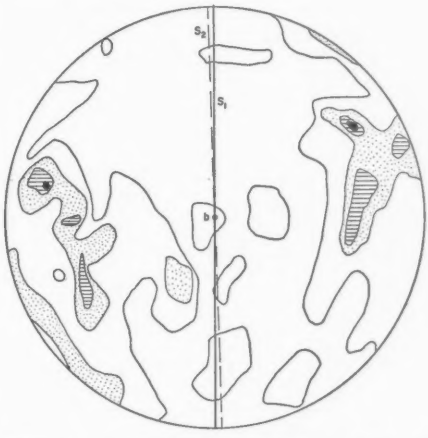


FIGURE 10.—EQUAL-AREA PLOT OF QUARTZ IN THE *A* SERIES

Shows 257 optic axes of quartz in biotite schist (G6). Rotated to make lineation polar. Contours 4-3-2-1 per cent, maximum 4 per cent.

Mineral Fabrics

Petrofabric diagrams were prepared for several rocks of the Hall Valley area. Sections were cut perpendicular to the strike of the foliation, and measurements were plotted on the lower hemisphere of an equal-area net. None of the measured thin sections showed linear parallelism of the contained minerals, but by giving consideration to the regional parallelism of linear minerals and minor fold axes as related to the orientation of the thin sections, it was possible to rotate the plots to make the *b* fabric axis polar in diagrams for all rocks except the migmatites.

Megascopic fabrics of the layered rocks on

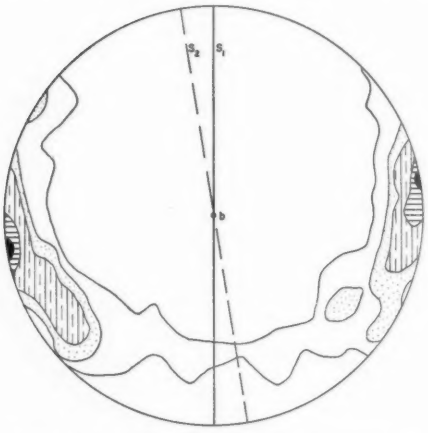


FIGURE 11.—EQUAL-AREA PLOT OF BIOTITE IN *B* SERIES

Shows 200 poles of cleavage in biotite in quartz-plagioclase-hornblende gneiss (H103). Rotated to make lineation polar. Contours 15-10-5-3-1 per cent, maximum 16.5 per cent.

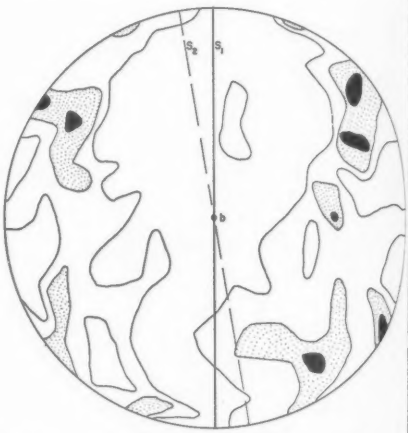


FIGURE 12.—EQUAL-AREA PLOT OF QUARTZ IN THE *B* SERIES

Shows 230 optic axes of quartz in quartz-plagioclase-hornblende gneiss (H103). Rotated to make lineation polar. Contours 3-2-1 per cent, maximum 3.4 per cent.

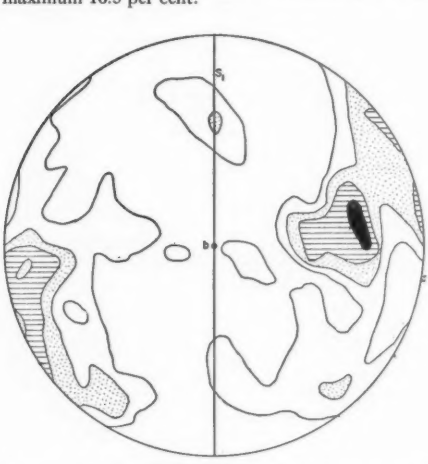


FIGURE 13.—EQUAL-AREA PLOT OF QUARTZ IN THE *A* SERIES

Shows 353 optic axes of large quartz in quartz-biotite gneiss (H33). Rotated to make lineation polar. Contours 4-3-2-1 per cent, maximum 4.5 per cent.

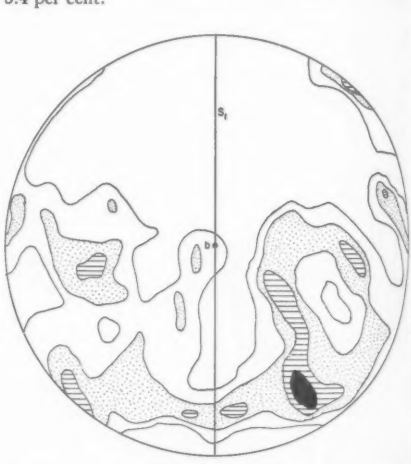


FIGURE 14.—EQUAL-AREA PLOT OF QUARTZ IN THE *A* SERIES

Shows 192 optic axes of small (relict) quartz grains in quartz-biotite gneiss (H33). Rotated to make lineation polar. Contours 4-3-2-1 per cent, maximum 4.6 per cent.

the limbs of the Handcart anticline display a pronounced monoclinic symmetry. Drag folds differ in number and intensity of folding from layer to layer. Gentle warps in some layers and isoclinal folds in other layers indicate that minor folding was concentrated in less competent layers between thick layers of more competent rocks. Biotite in mica-rich rocks wraps around many tight folds as well as open folds. Some layers contain ptygmatic folds in which mica is parallel to the bedding-plane foliation and oblique to intricately folded, cross-cutting veinlets of quartz and feldspar.

Petrofabric diagrams for clear biotite flakes

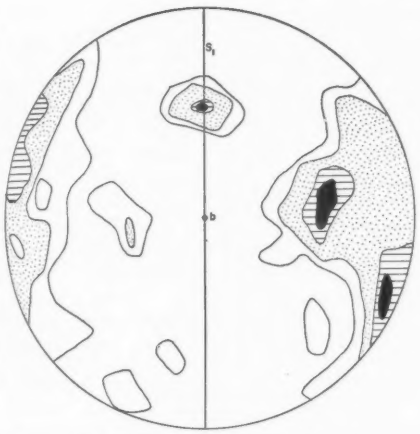


FIGURE 15.—EQUAL-AREA PLOT OF QUARTZ IN *B* SERIES

Shows 250 optic axes of large quartz grains in quartz-biotite gneiss (F37). Rotated to make lineation polar. Contours 5-4-2-1 per cent, maximum 6 per cent.

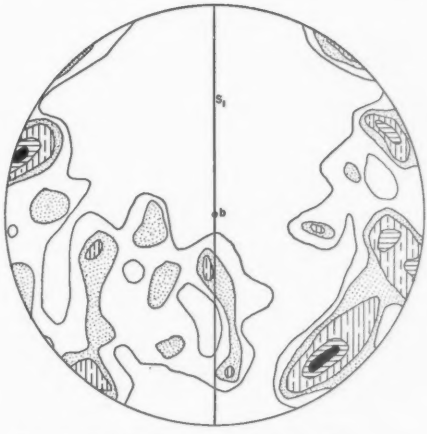


FIGURE 16.—EQUAL-AREA PLOT OF QUARTZ IN *B* SERIES

Shows 130 optic axes of small (relict) quartz grains in quartz-biotite gneiss (F37). Rotated to make lineation polar. Contours 5-4-3-2-1 per cent, maximum 5.3 per cent.

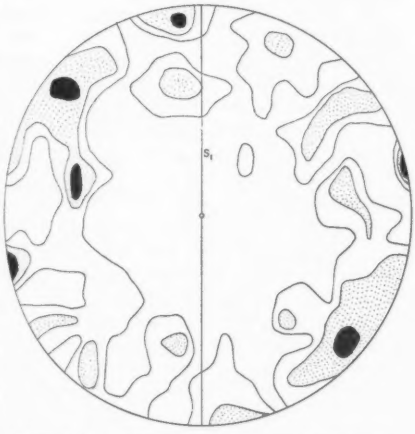


FIGURE 17.—EQUAL-AREA PLOT OF QUARTZ IN MIGMATITE

Shows 150 optic axes of small (relict) quartz grains in quartz-biotite gneiss (PS63). Section at right angles to strike of foliation. Contours 3-2-1 per cent, maximum 4 per cent.

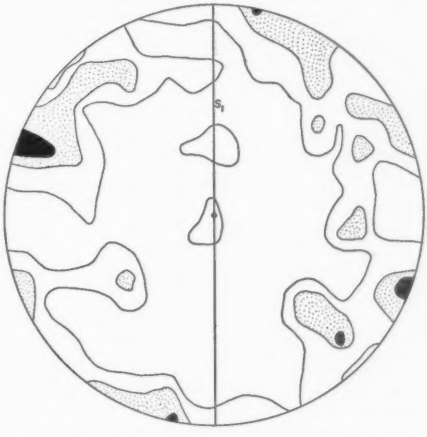


FIGURE 18.—EQUAL-AREA PLOT OF QUARTZ IN MIGMATITE

Shows 322 optic axes of large quartz in quartz-biotite gneiss (PS63). Section at right angles to strike of foliation. Contours 3-2-1 per cent, maximum 3.4 per cent.

(Figs. 9, 11) conform to the megascopic fabrics and show a monoclinic fabric in which an S plane for the micas is rotated somewhat with respect to bedding-plane foliation (S_1). Plots of quartz c axes for the same rocks (Figs. 10, 12) show an imperfect monoclinic symmetry with a twofold symmetry axis coincident with the *b* fabric axis. Girdles are poorly developed, and interpretation of the diagrams is not unequivocal, but correlation of the plots with megascopic fabrics indicates both laminar slip and some rotation during metamorphic recrystallization. Helicitic structures are present in some sillimanite bundles and confirm rotation

during crystallization. The fact that the biotite mica wraps around many tight folds suggests that much of the fabric is relict and preserves parallelism of platy minerals originally present in the sediments.

To test the idea that relict fabrics might be present diagrams were made for two types of quartz observed in many samples. Figures 13–18 compare orientations of scattered, small, round quartz grains enclosed in larger grains of mica and feldspar and larger, more abundant, recrystallized quartz grains. Less symmetry in the plots for the small quartz grains as compared with the larger quartz grains and markedly dissimilar contour patterns strongly indicate that the small grains are relict and were protected from rotation and recrystallization by the enclosing minerals.

Conspicuous bedding-plane foliation, biotite-mica wrapped around drag folds, poorly developed monoclinic fabrics in recrystallized quartz, and the presence of relict quartz grains support the conclusion that metamorphic recrystallization reached its maximum only after the sedimentary rocks had already been somewhat deformed. Elevation of temperatures to a maximum in the late stages of deformation not only promoted recrystallization in a stressed environment but, for rocks of low melting temperatures, also promoted mobilization and/or plastic flow.

Comparison of small and large quartz grains from migmatite southeast of North Fork fault (Figs. 17, 18) indicates that relict quartz survived not only metamorphic reconstitution of the sedimentary rocks but also later migmatization and granitization.

Summary

Correlation of field and laboratory data indicates the following Precambrian and later history for the Hall Valley area:

(1) Precambrian sedimentation resulted in the deposition of a thick series of interlayered coarse- and fine-grained clastic sedimentary rocks and impure calcareous rocks, probably in a subsiding basin. The location and depth of the floor of the basin is unknown because the lowest recognizable metamorphosed sedimentary unit grades downward and laterally into migmatized and granitized rocks. Quartzose sandstone was the dominant rock type in the lowest identified unit. Strata at intermediate levels consisted of shales or mudstones, argillaceous sandstones and arkoses, and impure limestones and dolomites. The highest observed unit in the series, which now consists primarily of quartz-biotite gneiss and quartzite, probably consisted of arkose, argillaceous sandstones, and quartzose sandstones. Some of the argillaceous clastic rocks may have had the compositions and textures of graywackes or subgraywackes.

A period of uplift and erosion occurred after deposition of this series. Several of the previously deposited sedimentary layers were partly eroded, and a laterally extensive surface of angular unconformity developed.

(2) Sedimentation resumed and resulted in deposition of a thick series of clastic rocks, especially arkoses and argillaceous sandstones, intercalated with clastic material of probable basaltic composition. Lenticularity characterized the deposition and indicates rapid accumulation of materials in a basin. Some of the layers in the higher portions of the series may have formed by reworking of older sedimentary rocks. The top of the series above the unconformity was not observed in the Hall Valley area.

(3) After a time interval of unknown duration and at depths that probably were moderate to considerable, the rocks in both the *A* and *B* series were subjected to compressive forces, and the northwest-trending Handcart anticline and subsidiary folds and faults began to form. At some stage in the deformation temperatures became high enough to initiate recrystallization of the sedimentary rocks, and as the thermal maximum was reached then were reconstituted into high-grade metamorphic rocks. Petrofabric analysis and helicitic structures indicate rotation and laminar slip of some of the mineral components during recrystallization and suggest simultaneous regional deformation and recrystallization. Mica wrapped around tight drag folds, conspicuous bedding-plane foliation, and relict minerals indicate that much of the original fabric in the sedimentary rocks survived metamorphism. Metamorphic recrystallization, according to this interpretation, probably coincided with only the latter stages of deformation.

(4) Renewed crustal disturbance caused extensive dislocation of previously metamorphosed rocks at depth along the northeast-trending North Fork fault. Movement along the fault produced a wide, complex zone of breccia, recrystallized mylonite, and flaser gneiss. Foliation northwest of the fault

almost perpendicular to foliation southeast of the fault and indicates dislocation of large magnitude along the fault. Minor cross folds northwest of the fault may have formed at the same time.

(5) Later than the formation of the North Fork fault, the foliated rocks southeast of the fault and, to a lesser extent, the rocks northwest of the fault were converted into migmatites and granitic rocks by metasomatism. Chemical analyses and petrographic studies indicate that granitization was accompanied by introduction of K_2O + Na_2O and simultaneous removal of MgO + FeO. Probably CaO was displaced; concentrations of dark minerals and more calcic plagioclases near the outer fringes of the migmatized areas suggest migration of cafemic components outward from centers of granitization into a poorly defined basic front. Migmatization and granitization were selective and did not notably affect highly quartzose or highly calcic layers. Chlorite formed from biotite, hornblende from pyroxene, turbid biotite associated with clear biotite, and other mineral changes in the nonmigmatized metamorphic rocks northwest of the North Fork fault may have been caused by penetration of the rocks by the same solutions that caused migmatization and granitization southeast of the fault.

(6) A body of Boulder Creek granodiorite was intruded into the northeast portion of the Hall Valley area and appears to cut across structures in the migmatites and granitic rocks. The migmatites and granitic rocks may be genetically related to the granodiorite, but evidence for this is not conclusive.

Granitic rocks superficially resembling Silver Plume granite seem to have developed by metasomatism of the metasedimentary rocks and, on a small scale, by local injection of mobilized quartzo-feldspathic rocks. Large bodies of typical Silver Plume granite are exposed east and south of the Hall Valley area but could not be traced into the area.

(7) The later Precambrian and post-Cambrian history up to the time of the Laramide revolution could not be determined from local evidence. The Laramide revolution, in late Mesozoic and early Tertiary, caused major structural dislocations in the Front Range and adjacent areas. The principal recognizable manifestations of Laramide activity in the Hall Valley area are the formation of small mineralized faults and the intrusion of numerous small bodies of porphyry.

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Manuscript Received by the Secretary of the Society, July 7, 1958

Appendix. Descriptions of Units in *A* Series and *B* Series

(In order of decreasing age. Letter symbols used on Plate 4 in parentheses.)

A series

1. *Quartz schist* (qs). Upper contact sharp, lower contact not observed. This unit is the lowest unit of the *A* series exposed in the Hall Valley area. Lower portion is covered or grades into migmatized or granitized rocks. Dominantly a light-colored, closely laminated quartz-rich schist containing numerous interlayers of quartz-muscovite-sillimanite schist, dark-gray quartz-sericite schist, and quartz-biotite gneiss. Section grades laterally into a sequence containing abundant quartz-biotite gneiss. Exposures are generally poor. Thickness at least 2300 feet.

The quartz schist consists dominantly of crushed, partly recrystallized quartz and abundant fine-grained sericite which formed in part from sillimanite. The sericitization may have resulted in part from hydrothermal solutions associated with nearby porphyry intrusions of Tertiary age.

2. *Lime-silicate rock* (lsi_1). Gradational contacts above, sharp contact below. Complexly interlayered hornblende-plagioclase schist and gneiss, hornblende schist, pyroxene rock, lime hornfels, and layers of calcite and quartzite. Removal of calcite by weathering yields a dull green, layered, porous rock (Pl. 2, fig. 1). Boudins of pyroxene rock rimmed by hornblende are common. Pegmatite and aplite dikes and sills locally abundant. Thickness 300–600 feet.

3. *Biotite-sillimanite gneiss* (bsi). Gradational contacts above and below. Consists of augen biotite-sillimanite gneiss, biotite-sillimanite schist and gneiss, muscovite-sillimanite schist, and biotite schist. A few thin layers of hornblende-plagioclase gneiss and schist are present. Augen become more numerous toward areas of pegmatite or migmatite. Milky lenses and streaks of sillimanite and large, lustrous flakes of biotite are characteristic. Abundant minerals are quartz, microcline, intermediate plagioclase, biotite, sillimanite, and muscovite. A fine-grained biotite schist marks the lower limit. Thickness 1000–1100 feet.

4. *Quartz-biotite gneiss* (qb_1). Gradational contacts above and below. A light-gray quartz-biotite gneiss consisting dominantly of quartz, microcline, sodic to intermediate plagioclase, and biotite. Thin layers containing hornblende and intermediate plagioclase locally abundant. Thickness 0–800 feet.

5. *Lime-silicate rock* (lsi_2). Gradational contacts above and below. Dark hornblende-plagioclase schist and gneiss containing light thin layers of pyroxene and/or calcic plagioclase and layers rich in quartz and/or potassium feldspar. Thickness approximately 400 feet.

6. *Quartz-biotite gneiss* (qb_2). Gradational contacts above and below. Light-gray, medium-grained quartz-biotite gneiss containing thin layers of hornblende-plagioclase gneiss and schist and biotite schist. Partly truncated by Hall Valley unconformity. Dominant minerals are quartz, plagioclase, microcline, and biotite. Thickness 2200–2500 feet.

7. *Lime-silicate* rock (lsi_3). Gradational contacts above and below. Complex mineralogy and fabric. Consists of hornblende-plagioclase gneiss and schist, pyroxene rock, amphibolite, lime hornfels, skarn, marble, thin quartzite layers, and layers rich in quartz, microcline, and mica. Boudins of pyroxene rock locally abundant (Pl. 2, fig. 2). Locally contains numerous aplite or pegmatite bodies. Truncated by unconformity at base of *B* series. Thickness 0–600 feet.

8. *Quartz-biotite gneiss* (qb_3). Gradational lower contact. Upper portion truncated by Hall Valley unconformity. Basal portion is dark gray and rich in biotite. Upper portions of unit light gray. Numerous muscovite aplite bodies just below unconformity. Middle of section contains abundant gray quartzite lenses and layers. Quartz, biotite, microcline, and sodic to intermediate plagioclase are dominant minerals. Thickness 0–1800 feet.

Angular unconformity

B series

1. *Plagioclase-hornblende-biotite gneiss* (phb_1) and *augen quartz-biotite gneiss* (au). Unit unconformably overlies truncated units of *A* series. Upper boundary gradational. Unit is conspicuously foliated and contains alternating thin and thick layers of plagioclase-hornblende gneiss, plagioclase-hornblende-biotite gneiss, quartz-plagioclase-hornblende gneiss, and quartz-biotite gneiss (Pl. 3, fig. 1). Thick lenticular bodies of coarse-grained augen gneiss are present in portions of the unit. Microcline forms the augen and is also abundant, together with quartz and biotite, in the matrix. Thickness about 1700 feet.

2. *Hornblende-plagioclase gneiss* (hp). Dark hornblende-plagioclase gneiss with thin interlayers of quartz-plagioclase-hornblende gneiss, plagioclase-hornblende-biotite gneiss, and minor quartz-biotite gneiss. Rocks locally very coarse-grained. Thickness 700–800 feet.

3. *Quartz-biotite gneiss* and *quartz-plagioclase-hornblende gneiss* (qbph). Gradational contacts above and below. Alternating thin layers of dark hornblende-plagioclase-biotite gneiss, thick and more abundant layers of quartz-plagioclase-hornblende gneiss containing abundant plagioclase and

less microcline. Lateral and vertical variation in fabric and mineralogy are noteworthy. Thickness 400–500 feet.

4. *Plagioclase-hornblende-biotite gneiss* (phb_2) and *quartz-biotite gneiss* (qb). Dominantly dark, conspicuously layered plagioclase-hornblende-biotite schist and gneiss containing intercalated layers of hornblende-plagioclase gneiss and light layers rich in calcic plagioclase. Thick and thin layers and lenses of medium- to coarse-grained quartz-biotite gneiss rich in intermediate plagioclase and/or microcline are locally abundant. Lateral and vertical variation in composition and thickness of layers characteristic of entire unit. Thickness 1200–1400 feet.

5. *Quartz-biotite gneiss* (qbg). Top not observed. Grades into underlying unit. Dominantly a conspicuously foliated quartz-biotite gneiss containing abundant quartz, microcline, oligoclase, and biotite. Thin layers of plagioclase-hornblende-biotite gneiss locally abundant. Thickness not known but probably exceeds 1500 feet.

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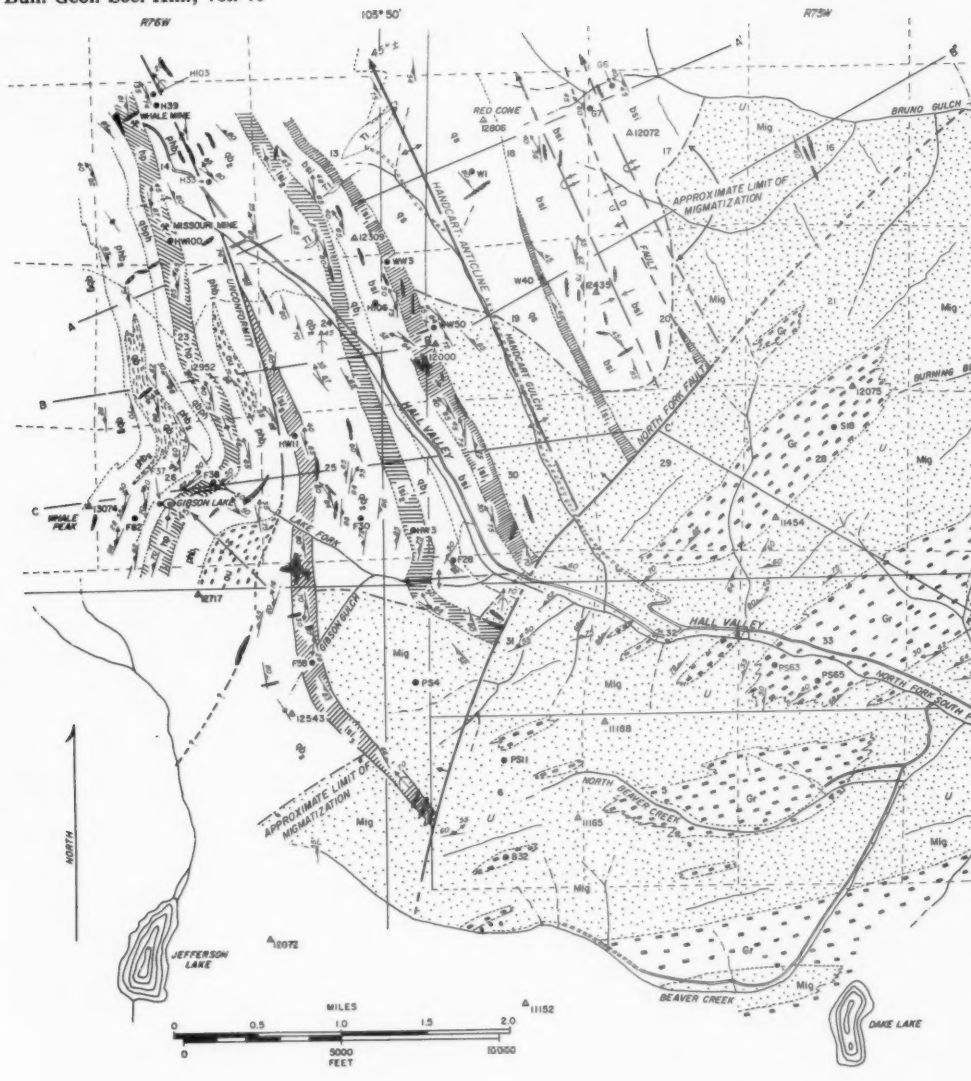
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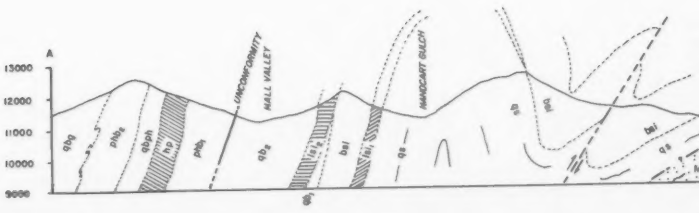
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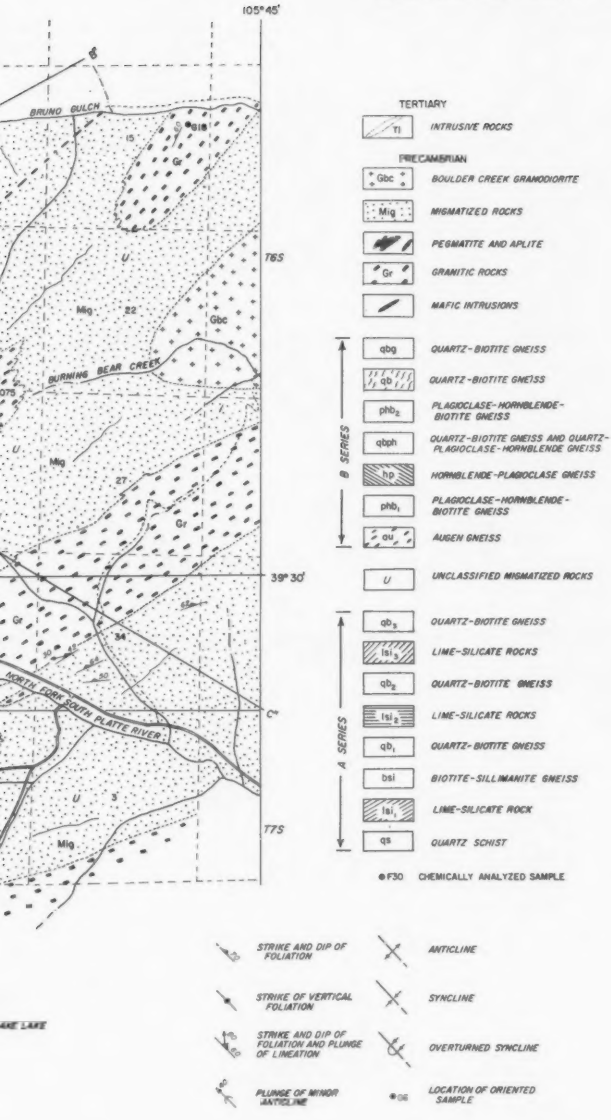
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INTRUSIVE ROCKS
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Gbc
BOULDER CREEK GRANODIORITE
Mig
MIGMATIZED ROCKS
PEGMATITE AND APLITE
Gr
GRANITIC ROCKS
MAFIC INTRUSIONS
B SERIES
qbg
QUARTZ-BIOTITE GNEISS
qb
QUARTZ-BIOTITE GNEISS
phb2
PLAGIOCLASE-HORNBLENDE-BIOTITE GNEISS
qbph
QUARTZ-BIOTITE GNEISS AND QUARTZ-PLAGIOCLASE-HORNBLENDE GNEISS
hp
HORNBLENDE-PLAGIOCLASE GNEISS
phb1
PLAGIOCLASE-HORNBLENDE-BIOTITE GNEISS
au
AUGEN GNEISS
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UNCLASSIFIED MIGMATIZED ROCKS
A SERIES
qb3
QUARTZ-BIOTITE GNEISS
lsi3
LIME-SILICATE ROCKS
qb2
QUARTZ-BIOTITE GNEISS
lsi2
LIME-SILICATE ROCKS
qb1
QUARTZ-BIOTITE GNEISS
bsi
BIOTITE-SILLIMANITE GNEISS
lsi1
LIME-SILICATE ROCK
qs
QUARTZ SCHIST
F30 CHEMICALLY ANALYZED SAMPLE
STRIKE AND DIP OF FOLIATION
STRIKE OF VERTICAL FOLIATION
STRIKE AND DIP OF FOLIATION AND PLUNGE OF LINEATION
PLUNGE OF MINOR ANTICLINE
ANTICLINE
SYNCLINE
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AKE LAKE
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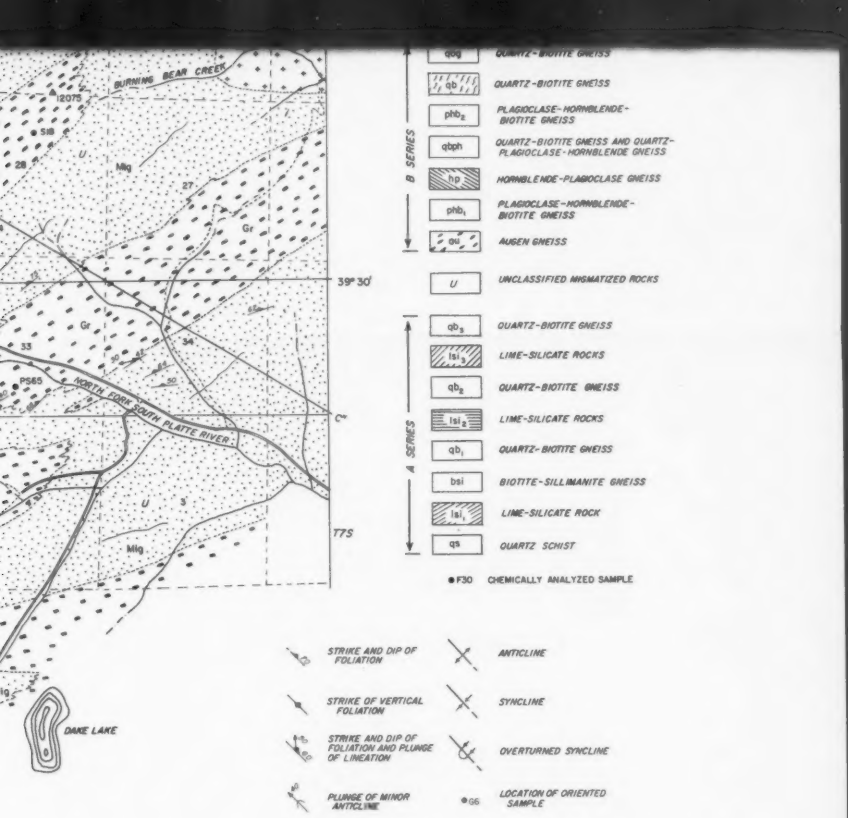
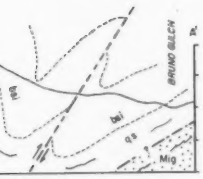
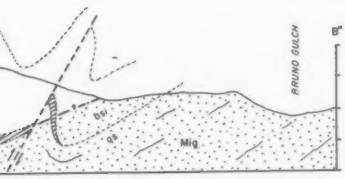
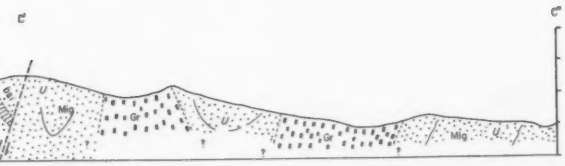
GEOLOGIC MAP AND CROSS SECTIONS OF HALL VALLE









VALLEY AREA, FRONT RANGE, COLORADO

Short Notes

BULLETIN OF GEOLOGICAL SOCIETY OF AMERICA
VOL. 70, PP. 1245-1246, 1 FIG., 1 PL. SEPTEMBER 1959

AGE OF LAVA FLOWS ON HALEAKALA, HAWAII

BY GROTE REBER

During 1954 and 1958 the writer examined the lava flows on the southwest side of Haleakala, Maui, Hawaii. Figure 1 shows their approximate location and names. The Keonehunehune flow originates in a nameless crater, so the name of an outstanding near-by crater was chosen. The southwest rift of Haleakala is studded with craters. Most seem to be cinder cones only, with no lava flows. Apparently most of the eruptions were violent and short. The Kamahina, Keonehunehune, and Kalua o Lapa flows are single. The remaining ones are complexes of several flows. At least two more recent flows originate near the 1500-foot level east of the map area and flow into the ocean. Also there are several recent flows inside Haleakala crater near the west end and from the center of the north inside. None of these was examined.

According to records, only the flow of Kalua o Lapa was seen by man. Stearns and Macdonald (1942, p. 103-107) given two accounts which point to a date of about 1750 A.D. I independently encountered the same Hawaiian legend from a Mrs. Kaheka Swift who incorrectly attributed it to the Kamahina flow. The lower part of the Kamahina flow is buried by the Kalua o Lapa flow. Mrs. Swift provided a good genealogy back to the original observer. To make the date come out 1750 it is necessary to assume 27 years for an average Hawaiian generation. This seems a bit too much. Perhaps 25 years would be better, giving a date of 1762. There seems little doubt that this flow occurred 200 ± 15 years ago.

The purpose of examining the flows was to find places where the lava had engulfed a tree or log. These are marked on the map. Most of the flows were not very hot, as they were aa or clinker tumbling along. Underneath the aa were small puddles of liquid pahoehoe which occasionally solidified without being broken up. About 500 to 1000 years ago the slope of the mountain above 2000 feet must have been covered by a forest of huge trees because tree moulds 3 to 6 feet in diameter were found on the Kamahina, Keonehunehune, and Makua flows. Because the lava was cool, these logs were charred only an inch or so deep on Keonehunehune and Makua flows. However, the Kamahina flow provided great quantities of hot thin lava which set like concrete several feet deep. Under this, tree roots several inches in diameter were completely carbonized.

Figure 1 shows the large tree mould found at the south edge of Kamahina flow. Many smaller tree moulds are in the environs. Figure 2 shows the large tree mould at the east edge of Makua flow. Figure 3 shows the place where log was engulfed by Keonehunehune flow. Figure 4 shows the half tree mould on the Pimoe flow. The lava was a small pool of pahoehoe which ran out from under the aa. It was nearly spent and congealed just as it half surrounded a tree about a foot in diameter. This flow is very black and sharp and jagged. It is a small one over part of a complex of many old flows. The charcoal is mostly carbonized root bark taken from under the slab of lava in a streak about 3 feet long. Apparently the root lay along the top of the ground near the trunk of the tree.

The charcoal samples were analyzed in October 1958 and Table 1 gives the results. "The Pimoe sample actually had a higher radiocarbon content than our modern standard which is wood historically dated as being formed in 1890." (Milton Trautman, Isotopes, Inc., personal communication.) A severe earthquake occurred on Maui in 1938. Perhaps this recent Pimoe flow was part of the same disturbance. The flow could easily have been overlooked in the wilderness as no one lives within several miles of it.

Minor eruptions still occur on Haleakala every few hundred years. Several more flows remain to be dated. Once dates are established it will be profitable to seek out puddles of pahoehoe. Contained therein will probably be magnetic particles which crystallized at a position aligned with the earth's magnetic field when the lava congealed. In this manner it may

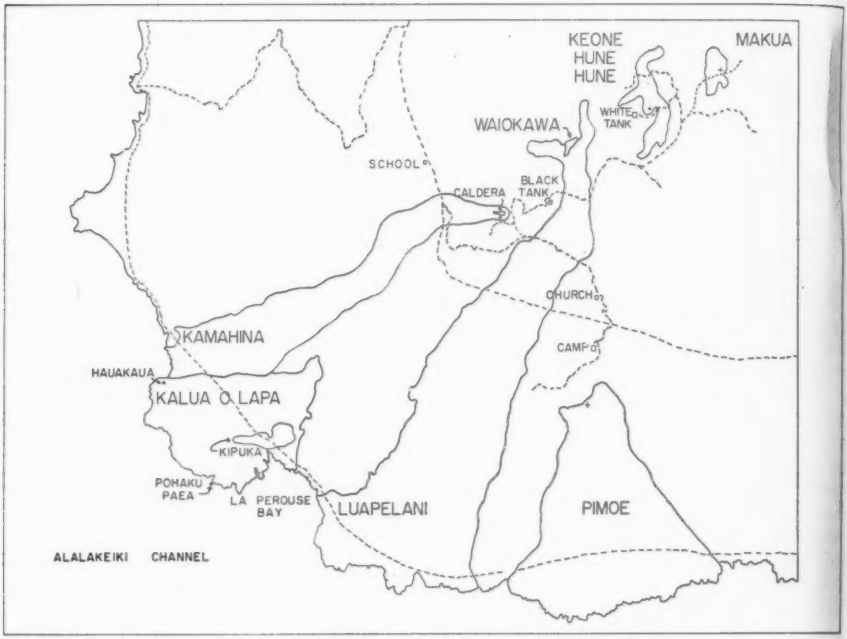


FIGURE 1.—MAP OF RECENT LAVA FLOWS ON LOWER PART OF SOUTHWEST RIFT OF HALEAKALA
Location of charcoal finds marked by + (1 inch = 1¾ miles)

TABLE 1.—RADIOCARBON DATES OF CHARCOAL
(Analyses by Isotopes, Inc.)

Hawaiian names of flows	Age Years	Probable error Years
Kamahina.....	890	±170
Keonehunehune..	650	±140
Makua.....	590	±120
Kalua o Lapa....	200	±15
Pimoe.....	<100	?

be possible to secure a history of the direction of the earth's magnetic field in the central Pacific area. Such information could then be used to date still other flows around which no charcoal can be found. The small flow named Waiokawa appears to be quite recent. There are three vents which look rather similar to bessemer steel converters. A few feet down inside are flat floors where the lava congealed in a quiescent condition. These vents are scored inside by colored vertical streaks as though a giant cutting torch had been used. Much further work is needed, and a wide variety of opportunities is available.

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MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, FEBRUARY 26, 1959

PLATE 1.—TREE MOULDS

FIGURE 1.—View from northwest of large vertical tree mould at edge of Kamahina flow near telephone pole

FIGURE 2.—View from southeast of large horizontal tree mould near east end of path across Makua flow

FIGURE 3.—View from south of mould formed by small log on the Keonehunehune flow

FIGURE 4.—View from southeast of half tree mould in edge of slab of Pahoehoe on Pimoe flow

FIGURE 2

FIGURE 4

FIGURE 1

FIGURE 3

TREE MOULDS

BULLETIN OF GEOLOGICAL SOCIETY OF AMERICA
VOL. 70, PP. 1247–1248, 1 PL. SEPTEMBER 1959

NOMENCLATURE OF LOAD DEFORMATION IN TURBIDITES

BY HAROLD H. SULLWOLD, JR.

The use of "load casts" as a general term for structures resulting from a load of sand pressing unevenly into underlying mud has serious shortcomings. The cast is a third-order term. First came the load, then depression within the mud, and finally the cast, which is conspicuous only where bottoms of beds are well exposed.

It was evidently fortuitous that the workers who coined the phrases "flow cast" (Shrock, 1948, p. 156) and "load cast" (Kuenen, 1953, p. 1058) had experience with the latter group where old rocks were well indurated and cemented. Bed bottoms are seldom exposed in poorly consolidated or gently dipping rocks such as the Tertiary strata of California in which the usual view is in cross section. In these cases the waves, wisps, or plumes of mud which have squirted up into the sand between the load casts are commonly the most obvious features, yet the word "cast", in the sense of "throw", seems to apply to them also. If the term "load cast" is retained as defined, then other equally important and obvious structural products of the same process of deformation by load are left unnamed.

The writer proposes that the terms load pocket, load wave, and load fold be given equal status with load cast. The load pocket is the bulge of sand pressing into the underlying stratum. The load wave (wisp and plume are nearly as acceptable) is the salient curved unevenness of underlying material which appears to have been squirted up into the superjacent turbidity-current deposit. The wave shapes vary from gentle upward bulges similar to ripple marks in cross section (Pl. 1, fig. 1) to sharp concavo-convex attenuated shapes identical in cross section to breaking waves (P. 1, figs. 2, 4), even to the extent of spray. The load folds (Pl. 1, figs. 1, 3) are plications in the laminae of the underlying stratum which are obviously the result of pressure from the unequal load of the overlying load pockets and waves. These folds are not everywhere evident, because commonly no laminae are present, but where they can be seen they closely follow the base of the loading bed and die out downward, generally within 1–2 inches. This requires flowage and therefore a rather fluid state of the bottom sediment upon which the turbidity current is depositing. Extreme fluidity is implied by the more attenuated load waves which in some exposures seem to trail off imperceptibly into the overlying sand.

In the upper Miocene Modelo formation on the north slope of the Santa Monica Mountains, Los Angeles County, California, load deformation is seen naturally only in cross section. One must dig under the gently dipping sandstone beds to view the load casts (Pl. 1, fig. 5). In determining the direction of these linear features it is much easier to work with the load folds, stripping off a small overburden to reveal their axes (Pl. 1, fig. 6). In this area cross-bedding is the most useful oriented feature, and a recent study (Sullwold, manuscript) revealed that the Modelo formation was deposited as a delta in water about 3000 feet deep at the mouth of a submarine canyon. Many of the load folds are oriented parallel to the current directions (as determined from cross-bedding), but the load waves are tipped at right angles thereto and therefore do not indicate current direction. Birkenmajer offered an ingenious explanation for a similar situation in the Carpathian Flysch. He proposed that if the current were not travelling directly downslope (its course modified perhaps by Coriolis parameter, oceanic currents, levee topping, or momentum at slope changes) any post-depositional downslope gravity slump or flowage would produce uniform tipping of load waves which would appear to be at right angles to the linear load folds or load casts. This notion was not thoroughly checked by the writer in the Modelo formation.

A possible, hitherto unrecorded, origin for convolute bedding can perhaps be postulated in the light of load folds. If, soon after the birth of a series of load folds, the loading bed along with its load pockets were removed by submarine erosion, further deposition would conceal the obvious origin of the remaining load folds. These folds might then resemble convolute bedding, might be called convolute bed-

ding, indeed might *be* convolute bedding. This possibility is illustrated in Figure 3 of Plate 1.

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Manuscript Received by the Secretary of the Society, March 14, 1959

Plate 1.—LOAD DEFORMATION IN MODELO FORMATION, UPPER MIOCENE, SANTA MONICA MOUNTAINS, CALIFORNIA

All photographs by the writer

Figure 1.—Graded sandstone (arkosic wacke) overlying shale. Downward protuberances of the sandstone are here defined as load pockets, upward protuberances of the underlying shale as load waves, and resulting bending of the laminae in the shale as load folds. The surface of contact between sandstone and shale, if exposed to view, would reveal load molds when viewed downward toward the shale and load casts when viewed upward toward the sandstone. The writer objects to the use of the term "load cast" as a name for the entire phenomena. Knife and main blade are 6 inches long.

Figure 2.—Load waves (top layer of dark band) showing rather extreme wispiness and uniformity of inclination. Sandstone above and below is graded.

Figure 3.—Load pockets, load waves, and load folds in band between pencil and knife. Sandstone beds above and below are graded. If the top of the deformed sequence had been planed off, obliterating the nature of its origin, the remaining load folds would be similar to, if not equal to, convolute bedding. Fold nearest pencil has deeper roots, was probably accentuated by sliding or slump along darkest layer.

Figure 4.—Rather extreme load wave (for this area). Here both the wave and pocket are sandstone; the wave is finer-grained and lighter-colored.

Figure 5.—Load casts at the bottom of a thick sandstone bed. Exposures of the bottoms of sandstone beds are very rare in the area. This one had to be dug out.

Figure 6.—Linear load fold revealed after removing the loading sandstone and part of the shale along a plane of lamination. The pencil is along the axis of a second less obvious fold.

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FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

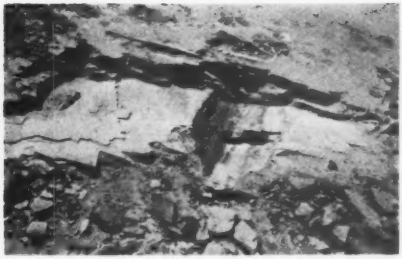

FIGURE 6

LOAD DEFORMATION IN MODELO FORMATION, UPPER MIOCENE, SANTA MONICA MOUNTAINS, CALIFORNIA

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 70, 2 FIGS., 1 PL., PP. 1249–1252 SEPTEMBER 1959

DEVONIAN SYSTEM IN THE PAHRANAGAT RANGE, SOUTHEASTERN NEVADA

BY ANTHONY RESO AND CAREY CRONEIS

One of the most significant sections of Devonian strata in western North America is exposed on the western slopes of the Pahranagat Range in southeastern Nevada. Because of the potential importance of this unusually thick and nearly complete Devonian section in the interpretation of Mid-Paleozoic sedimentation and paleogeography, some generalized results of field work are presented, and preliminary correlations are suggested in advance of a more detailed report.

The type section and faunal zones for the Devonian strata of the Western United States were established in 1940 by C. W. Merriam whose classic report soon became the basic reference for all "Western Devonian" investigations. This resulted from the fact that Merriam's type section was the most nearly complete, relatively undisturbed Devonian sequence (4500 feet) described up to that time. Merriam (1940, p. 40–41) pointed out, however, that Devonian sections in the Pahranagat Range may have an even greater thickness although they had received little attention since visited by Walcott at the time of the Eureka Survey (Hague, 1892, p. 196). A faunal list for the Upper Devonian of the Pahranagat Range also contains species not typical of Merriam's type section. Hence Merriam concluded, "that a study of this fine Pahranagat section would be of great significance in furtherance of knowledge of the Western Devonian." Correspondence with Dr. Merriam and with Dr. Vernon Scheid of the Nevada Bureau of Mines, confirmed the fact that relatively little additional work has been done on this specific Western Devonian problem.

A major study of the Devonian stratigraphy and paleontology of the Pahranagat Range has been undertaken as part of a general investigation of the geology of southeastern Nevada being developed by The Rice Institute. This preliminary note discusses some developments resulting from field studies during the summer of 1958 and answers specifically two basic questions concerning the Pahranagat Devonian raised by Merriam (1940, p. 41) which are: (1) What is the total thickness of the section? (2) Are beds of Nevada age (as restricted by Merriam), that is early and medial Devonian, present?

The writers thank The Geological Society of America for a grant from the Penrose Bequest, the American Association of Petroleum Geologists for support from Research Committee funds, and the Department of Geology, The Rice Institute, for additional financial assistance. Without this aid field work would not have been possible.

Helpful advice was received from Prof. R. L. Langenheim, Jr., of the University of California who has done reconnaissance studies in southeastern Nevada in recent years, and from Dr. John C. Osmond of the Gulf Oil Corporation, who measured a Pahranagat Devonian section in connection with his study of the Sevy and Simonson Dolomites (1954). The writers are also indebted to Mr. Lawrence S. Griffith for helpful co-operation and field assistance.

The Pahranagat Range is located in western Lincoln County, southeastern Nevada (Fig. 1). It is a typical Great Basin feature that extends about 40 miles north-south and has a maximum east-west width of approximately 12 miles. The town of Alamo, population 250, is located on the eastern side of the range in the White River Valley and with the exception of the small towns of Caliente, Panaca, and Pioche, 55 to 80 road miles to the northeast, is essentially the only community within a radius of 100 miles. The highest elevation in the Pahranagat Range is Mount Irish which rises to 8741 feet. Thus there is approximately a mile of differential relief in the area, the elevation at Alamo being 3450 feet. The Desert Valley on the western side of the Pahranagat Range is uninhabited, and there are only crude trails permitting access to the most important and complete Devonian and other Paleozoic exposures.

The maximum composite thickness of the Devonian system in the Pahranagat Range is approximately 6048 feet. For the purposes of mapping, this sequence was divided into five formations, employing the established terminology for eastern Nevada and Utah. These formations are, in ascending order and with maximum thicknesses: the Sevy formation (lower and probably middle Devonian) 1630

feet; the Simonson formation (middle Devonian) 1188 feet; the Guilmette formation (middle and upper Devonian) 2360 feet; the West Range limestone (upper Devonian) 410 feet; and the Pilot shale (upper Devonian and possibly lower Mississippian) 460 feet. The Sevy formation is underlain by the Silurian Laketown dolomite, and the Pilot shale is overlain by the Mississippian Joana limestone.

A relatively uncomplicated, apparently conformable Devonian section of 5428 feet is exposed in one large eastward-tilted block on the west slope of the Pahranagat Range approximately 6 miles south of Highway 25 (Fig. 1, location A; section, Fig. 2). This substantially confirms a Pahranagat Range thickness reported by Hague (1892, p. 200) and referred to by Merriam (1940, p. 41). This one general field locality displays maximum thicknesses for the Sevy, Simonson, and Guilmette formations as well as 250 feet of the Pilot shale. An upper Devonian unconformity is believed responsible for the absence of the West Range limestone and part of the Pilot shale at this locality. The two latter units, however, attain a combined thickness of 870 feet at a locality about 9 miles to the northeast on the east side of the Pahranagat Range (Fig. 1, location B). The relationships are suggested in Figure 2.

The Devonian sections on the west side of the Pahranagat Range are possibly the most spectacular and complete exposures of Devonian strata thus far measured in western North America (Pl. 1). They exceed the thickness of

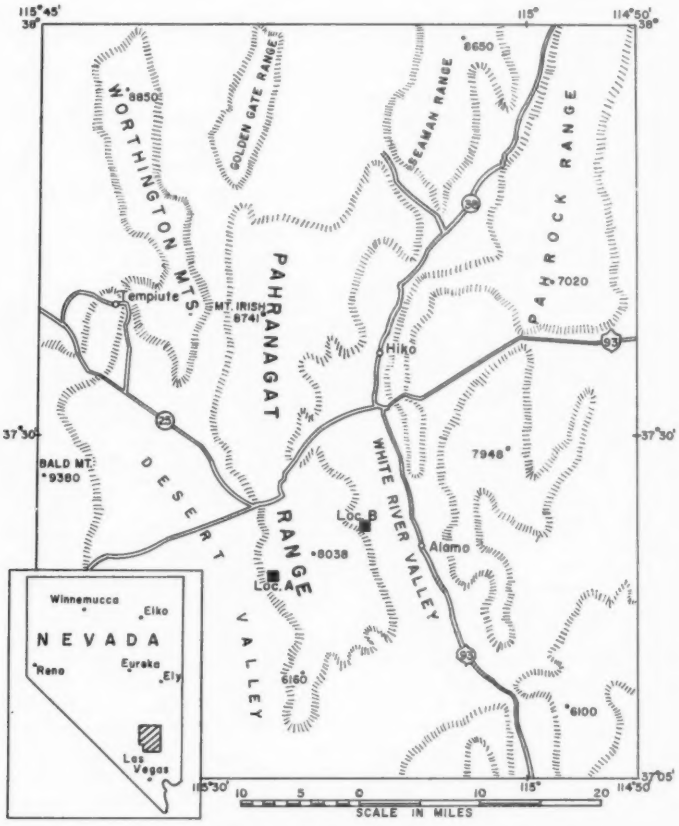

FIGURE 1.—INDEX MAP SHOWING THE PAHRANAGAT RANGE AND SURROUNDING AREA, LINCOLN COUNTY, NEVADA

DEVONIAN SYSTEM IN THE PAHRANAGAT RANGE, SOUTHEASTERN NEVADA

Mile-thick Devonian section on west side of Pahranagat Range, Lincoln County, southeastern Nevada, as seen looking north from a spot on the somewhat thicker, but otherwise similar, section referred to in Figure 2 as Location A. The latter section is approximately 2 miles south of the ridge illustrated. Section shown is about 4 miles south of Highway 25 which can be seen trending northwestward across the Desert Valley just above the letter *a* in left of photograph.

The section illustrated dips slightly north of east, from more than 45° to less than 30° from west to east as a major fault is approached.

a. Contact of Laketown dolomite (Silurian) and Sevy dolomite (Lower and Middle Devonian)
a-b. Sevy formation, approximately 1500 feet thick in this section
b-c. Simonson formation (Middle Devonian)
c. Approximate location of *Stringocephalus* zone
c-d. Guilmette formation (Middle and Upper Devonian)
d-e. Pilot shale (Upper Devonian)
e. Contact of Pilot shale and Joana limestone (Mississippian)

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Merriam's type section by approximately 1000 feet. The composite thickness of the Devonian formations in the Pahranagat Range also is greater than that of the section described by

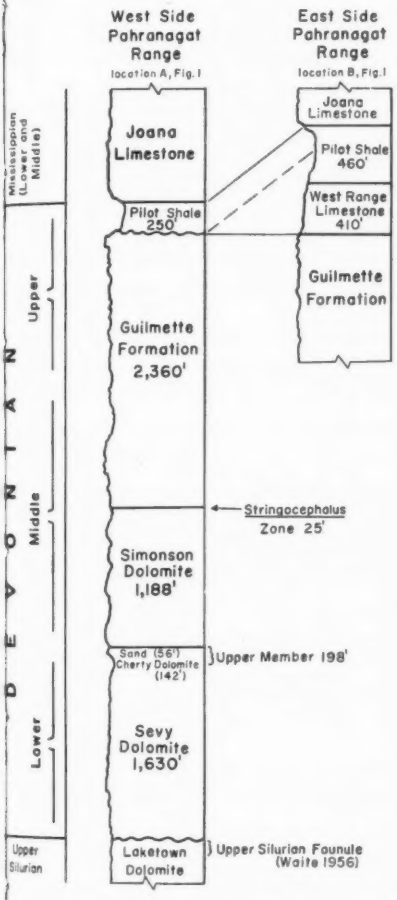

FIGURE 2.—GENERALIZED SECTION OF DEVONIAN FORMATIONS IN THE PAHRANAGAT RANGE, LINCOLN COUNTY, NEVADA

Nolan *et al.* (1956, p. 40–53) in the vicinity of Eureka, Nevada, and the exposures are less complicated structurally. An equally well exposed but thinner (5442 feet) composite Devonian section, however, has recently been measured in the Southern Egan Range of Nevada by Dr. Harold E. Kellogg of Columbia University (1959, personal communication).

All five members of the Nevada formation described by Nolan *et al.* (1956) have stratigraphic equivalents in the Pahranagat Range. The two lowest members of the Nevada formation, the Beacon Peak dolomite member and part of the overlying Oxyoke Canyon sandstone member, are probable correlatives of the Sevy formation in the Pahranagat Range. The Sevy formation consists of a uniform white-gray aphanitic dolomite and an upper sandstone member. Merriam's oldest Devonian faunal zone at the type section (regarded as at least as old as Oriskany) is believed equivalent to the Beacon Peak dolomite member of the Nevada formation (Nolan *et al.*, 1956, p. 46). The Sevy dolomite is lithologically identical to, and occupies the exact stratigraphic position as, the Beacon Peak dolomite member of the Nevada formation. The Sevy dolomite is therefore considered to be early Devonian; and its upper sandstone member, which is equivalent to part of the Oxyoke Canyon sandstone member of the Nevada formation, includes strata transitional between lower and middle Devonian (Nolan *et al.*, 1956, p. 47).

There is little question regarding the lower boundary of the Sevy formation in the Pahranagat Range. The base of the formation is marked by the distinct lithologic change between the underlying dark-gray phaneritic Laketown dolomite and the superjacent white-gray aphanitic Sevy dolomite. Upper Silurian brachiopods have been described by Waite (1956) from the Laketown dolomite in the Pahranagat Range. These commonly occur 50 to 136 feet below the base of the Sevy and may be utilized as an important marker on the west flank of the Range.

The boundary between the Laketown dolomite and the Sevy is considered to be unconformable in the Pahranagat area. The Laketown thins eastward with loss of a major portion of its upper member, including Waite's Upper Silurian brachiopod zone. Silurian–Devonian boundary studies, therefore, can be limited to the strata between the definite Silurian brachiopod faunule and the lowest beds of Sevy-type lithology on the west side of the Pahranagat Range, or in most places to much less than 150 feet of section.

The three upper members of the Nevada formation, the Sentinal Mountain dolomite member, the Woodpecker limestone member, and the Bay State dolomite member, may be correlated with the Simonson formation with the notable difference that the Woodpecker member is entirely a dolomite facies in the

Pahranagat area. The *Stringocephalus* fauna extends nearly throughout the Bay State dolomite member (Nolan *et al.*, 1956, p. 47). In the Pahranagat Range, however, the *Stringocephalus* zone may be used in field work to define the top of the Simonson formation. The diagnostic brachiopod apparently is restricted to about 25 feet of strata transitional from Simonson dolomite to the overlying limestone beds of the Guilmette formation (Fig. 2).

The Nevada formation attains thicknesses in central Nevada from 2448 feet at Lone Mountain (Merriam, 1940, p. 14; Merriam and Anderson, 1942, p. 1681) to an estimated 2900 feet in the latitude of the Phillipsburg mine (Nolan *et al.*, 1956, p. 42). The Sevy and Simonson formations are completely exposed along the west side of the Pahranagat Range and tend to thicken slightly southward to a combined maximum of approximately 2818 feet.

The Guilmette formation is a general correlative of the Devils Gate formation of Merriam but in the Pahranagat area it is characterized by lithologies, faunas, and thicknesses significantly different from the Devils Gate as described elsewhere. Members of the Devils Gate described by Nolan *et al.* (1956) are, however, present within the Guilmette section of the Pahranagat area.

The West Range limestone and Pilot shale attain maximum thicknesses on the east side of the Pahranagat Range (Fig. 2). The West Range contains a prolific upper Devonian brachiopod fauna. The upper 16 to 50 feet of the Pilot is represented by a black shale with included disc-shaped and round "limestone concretions." These strata are overlain by a 28-foot sequence containing an early Mississippian faunule. Thus the upper part of the Pilot shale, both in lithology and stratigraphic position, is strikingly similar to other ubiquitous North American black shales at or near the Devonian-Mississippian boundary.

The Devonian strata in the Pahranagat Range of southeastern Nevada includes all stages, with the possible exception of the Helderbergian, known throughout the Great Basin from Lower Devonian sediments to beds transitional to the Mississippian. The Devonian section also contains significant faunal zones which should facilitate regional correlations and contribute to the knowledge of Devonian paleogeography. Moreover, the sequence attains a thickness which apparently is maximum for the Great Basin and it provides new faunas which may eventually help perfect general North American Devonian correlations.

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MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, FEBRUARY 28, 1959